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# Preliminary Technical Report
# Submicron Measurement Error Analysis
# Evaluation of Physical and Metallurgical Properties of Materials

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November 8, 1964

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Preliminary Technical Report

on

Item 1. Submicron Measurement Error Analysis.

Item 1 Work Statement: Evaluate the physical and metallurgical properties of materials used in measuring engine construction to determine comparative suitability to submicron measuring. Materials to be considered are: Meehanite, steel, granite, aluminum, magnesium, and glass.

Submitted by:

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Task II. Item 1. Preliminary Technical Report.

The materials under study are:

1. Meehanite
2. Steel
3. Granite
4. Aluminum
5. Magnesium
6. Glass

The materials may be more precisely defined as follows:

Meehanite. A high quality grey cast iron. The composition and properties are much more closely controlled than common structural cast iron. Meehanite is available in a variety of grades and the properties vary widely with grade.

Steel. Available in an enormous variety of alloys. For our purposes a low carbon, wrought, structural steel is representative.

Granite. Natural quarried granite is available in pink, grey, and black. Black granite is reportedly the hardest, most uniform, and best quality so we have used it in the evaluations.

Aluminum. Tooling plate is specially formulated and fabricated for high stability and low residual stresses. The cast type 300 is slightly better than wrought type. Therefore, the properties of Alcoa type 300 cast aluminum tool and jig plate have been used in the evaluation.

Magnesium. Dow Alloy AZ 31 B is specially fabricated in tooling plate with high stability and low residual stresses. Alloying elements are 1% zinc and 0.45% manganese.

Glass. Fuzed quartz was selected as the glass best suited to measuring engine applications.

The properties covered in detail in this preliminary report are:

1. Modulus of elasticity (stiffness).
2. Density (weight).
3. Ratio of stiffness to weight.
4. Thermal conductivity.
5. Thermal coefficient of linear expansion.
6. Thermal capacity.
7. Ratio of thermal expansion to thermal capacity.



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1. Modulus of Elasticity (stiffness), E.

The modulus of elasticity is usually called Young's modulus and is a measure of the inherent stiffness of a material in tension or compression. It is the amount of force per unit area (stress in lbs/inch$^2$) required to affect a given deflection (strain in inches/inch). Since strain is a dimensionless ratio, the units of the modulus are in lbs/inch$^2$.

Typical values are:

| | | |
|---|---|---|
| Steel | 29.0 | x $10^6$ psi |
| Meehanite (cast iron) | 23.0 to 17.5 | x $10^6$ psi |
| Black Granite | 13.6 to 8.4 | x $10^6$ psi |
| Aluminum tooling plate | 10.3 | x $10^6$ psi |
| Magnesium tooling plate | 6.5 | x $10^6$ psi |
| Fuzed quartz | 4.4 | x $10^6$ psi |

Steel is the stiffest of the common structural materials. The stiffness of Meehanite cast iron is different for the different grades but is consistent within a given grade. Granite being a natural unrefined material, the stiffness varies with the composition of the material as quarried.

2. Density (weight), $\rho$.

The lighter weight materials are desirable for structure in order to reduce the total weight of a machine and to reduce deflections of individual members due to their own weight.

Typical values are:

| | |
|---|---|
| Magnesium tooling plate | .064 lbs/in$^3$ |
| Fuzed quartz | .079 lbs/in$^3$ |
| Aluminum tooling plate | .101 lbs/in$^3$ |
| Black granite | .110 lbs/in$^3$ |
| Meehanite cast iron | .257 lbs/in$^3$ |
| Steel | .283 lbs/in$^3$ |

3. Stiffness to Density Ratio, $E/\rho$.

Normally, the lighter weight materials also have a lower stiffness modulus. Since it is desirable to have high stiffness and low weight for a given structure, the ratio of these two properties will give a figure of merit for the material. The units of the ratio are:

$$\frac{\text{Young's Modulus in lbs/in}^2}{\text{Density in lbs/in}^3} = \text{inches}$$

Typical values of $E/\rho$ are:



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| | | |
|---|---|---|
| Steel | 102 | $\times 10^6$ inches |
| Aluminum tooling plate | 102 | $\times 10^6$ inches |
| Magnesium tooling plate | 102 | $\times 10^6$ inches |
| Black Granite | 77 to 123 | $\times 10^6$ inches |
| Meehanite cast iron | 68 to 89 | $\times 10^6$ inches |
| Fuzed quartz | 56 | $\times 10^6$ inches |

This interesting criterion shows that the design of a rigid structure will have the <u>same weight regardless of whether steel, aluminum, or magnesium are selected</u> for their inherent properties. Designing for a maximum stiffness-to-weight ratio, as required for most optical structures, is entirely different than designing for a maximum strength-to-weight ratio as is done in aircraft structure. Note also that granite, Meehanite, and quartz are less desirable materials from the standpoint of stiffness-to-weight ratio.

4. Thermal Conductivity, k.

The ability of a material to achieve a uniform temperature distribution throughout its volume in a minimum time is determined by its thermal conductivity. A high thermal conductivity is desirable if distortions of a structure due to a change in environment temperature are to be minimized. The thermal conductivity in cgs units is the amount of heat in calories which is transmitted per second through a plate one centimeter thick across an area of one square centimeter when the temperature difference is one degree centigrade. The thermal conductivity of pure copper, which is often used as a reference, is approximately 1.0 in cgs units.

Typical values are:

| | | |
|---|---|---|
| Aluminum tooling plate | .25 to .30 | cgs |
| Magnesium tooling plate | .18 | cgs |
| Steel | .15 | cgs |
| Meehanite cast iron | .14 | cgs |
| Fuzed quartz | .03 | cgs |
| Black Granite | .005 | cgs |

5. Thermal Coefficient of Linear Expansion.

The amount that a bar of material will expand linearly under a specified temperature change is determined by the thermal coefficient of linear expansion. The units are expressed as strain in inches/inch per degree centigrade. A low coefficient is desirable to maintain dimensional stability of a structure as the temperature of the structure varies.



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Typical values are:

| | | |
|---|---|---|
| Fuzed quartz | 0.5 | $\times 10^{-6}$ in/in/°C |
| Black Granite | 5.4 | $\times 10^{-6}$ in/in/°C |
| Aluminum tooling plate | 12.0 | $\times 10^{-6}$ in/in/°C |
| Steel | 12.0 | $\times 10^{-6}$ in/in/°C |
| Meehanite cast iron | 12.0 to 12.4 | $\times 10^{-6}$ in/in/°C |
| Magnesium tooling plate | 26.8 | $\times 10^{-6}$ in/in/°C |

Since granite and Meehanite have roughly half the thermal coefficient of linear expansion of steel and aluminum and less than one-quarter that of magnesium, they are much more desirable in this respect for optical structures. Fuzed quartz is most desirable of all by a factor of 10 and more.

6. Thermal Capacity.

The amount of heat required to raise the temperature of a unit mass of material one degree C. is determined by its thermal capacity. The thermal capacity of water, which is the standard, equals one. The units are in calories per gram. This can be converted to BTU per lb or watt-seconds per lb if desired. Heat capacity is important when heat is being pumped into a structure for example, by a motor or a lamp. For optical structures it is desirable that the thermal capacity by high so that it can absorb heat with a minimum of temperature rise.

Typical values are:

| | |
|---|---|
| Magnesium tooling plate | 0.246 cal/gram/°C. |
| Aluminum tooling plate | 0.214 cal/gram/°C. |
| Fuzed quartz | 0.188 cal/gram/°C. |
| Black Granite | 0.172 cal/gram/°C. |
| Meehanite cast iron | 0.119 cal/gram/°C. |
| Steel | 0.115 cal/gram/°C. |

7. Ratio of Thermal Coefficient of Linear Expansion To Thermal Capacity.

The ratio of thermal expansion to thermal capacity indicates the amount of strain produced in a material by the absorption of a unit amount of heat. The units are strain in inches/inch divided by calories/gram which equals gram/calories.

The ratio is a truer indication of desirability of a material than either thermal expansion or thermal capacity taken alone. A low ratio is desired so that a



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maximum amount of heat can be absorbed with a minimum of strain resulting in the structure.

Typical values per gram of material are:

| | | |
|---|---|---|
| Fuzed quartz | 2.7 | $\times 10^{-6}$ in/in/cal |
| Black Granite | 31.4 | $\times 10^{-6}$ in/in/cal |
| Aluminum tooling plate | 56.0 | $\times 10^{-6}$ in/in/cal |
| Meehanite cast iron | 100.9 | $\times 10^{-6}$ in/in/cal |
| Steel | 104.2 | $\times 10^{-6}$ in/in/cal |
| Magnesium tooling plate | 109.0 | $\times 10^{-6}$ in/in/cal |

Quartz clearly has the best thermal properties while Meehanite, steel, and magnesium are all about the same. Black granite is about three times as thermally stable and aluminum is about twice as thermally stable as the other metals. Thus, the rankings of desirability have changed compared to that obtained by considering only the thermal expansion coefficient.

8. Other Properties.

The strength of the materials under study is not a major consideration. In a structure designed for maximum rigidity the stresses are low.

The ductility (or its inverse, brittleness) of the materials is important as related to manufacturing ease and rough handling in use. Manufacturing ease will be discussed separately.

The damping characteristic of the materials is of considerable importance in optical structures, but data are essentially unavailable. A high damping factor is desirable so that the material will absorb or attenuate vibrations and prevent them from ringing through the structure. Certain construction techniques can be used to provide a dead or well damped structure. Construction techniques will be discussed separately at a later date.

One of the attributes claimed for magnesium, for granite, and for Meehanite is their high damping coefficients. Steel, of course, rings like a bell. Since this characterisitic is of importance, a further search will be made for data.

Corrosion resistance is also an important characteristic. Quartz and granite do not corrode under normal laboratory conditions and require no protection. Aluminum also requires no corrosion protection for measuring engine application. Its oxide forms a hard, tough impervious coating. Steel and Meehanite corrode readily and continuously unless well protected by paint, oil, or grease.



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Magnesium is highly susceptible to corrosion and difficult to protect. Dow has developed special finishes and treatments for corrosion protection of magnesium alloys. It is almost impossible, however, to protect clean working surfaces and the magnesium oxide is a fine, white, loose powder which can contaminate bearings and sliding surfaces.

Dimensional stability of the materials is of great importance but data are almost non-existent. Quartz and granite have excellent dimensional stability. For the metals, good stress relief treatments are essential to achieve good dimensional stability. Of the metals, cast iron is considered to have the best dimensional stability and aluminum jig plate next. The standing of steel and magnesium tooling plate is undetermined. Further search will be made for data on dimensional stability.

9. Fabrication.

Quartz is a non-structural material because of its high cost and extreme difficulty of fabrication. It can be shaped only by casting, sawing, grinding, sand blasting, or chipping. It can be joined only by clamping or fuzing. It cannot be threaded, riveted, or bolted without special precautions. It cannot be machined or welded.

Granite has all the same limitations and it cannot be cast. Its cost is so low, however, that it is economic to use it in large blocks as in surface plates.

Magnesium can be readily cast, machined, sawed, threaded, riveted, and bolted. It is seldom welded and in machining special safety precautions must be taken. Its cost is higher than the other metals, and it is more expensive to fabricate.

Meehanite can be cast, machined, and joined by all common methods. Due to abrasive tool wear, machining is a little slow and, therefore, a bit expensive. The basic castings, however, are inexpensive.

Aluminum can be cast, machined, and joined by all the common methods. The material cost is more expensive than steel or cast iron but machining is fast and cheap.

Steel is the most common structural material and generally the cheapest. It can be cast machined and joined by all common methods.

10. Summary.

For design of high stiffness to weight structures, as



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is required in most optical equipment, steel, aluminum, magnesium and certain formulations of Meehanite are equally efficient. The light weight advantage of magnesium and aluminum disappears when the modulus of elasticity is taken into account (see column 3 of Summary Tabulation). Magnesium is least desirable when its corrosion and cost are considered. Steel is most desirable from its cost and ease of fabrication, but aluminum has some advantage in its very high thermal conductivity which tends to reduce thermal distortions. When lamps and motors are involved, they act as localized heat sources and pump heat into the structure causing temperature gradients. Under such conditions, aluminum is the most desirable structural material.

When the principal limitation is space, not weight, steel is clearly the most desirable.

For design which requires optical flatness and straightness and no thermal expansion, quartz is the most desirable. Granite is second but is not as good as quartz by a factor of 10. The cost and availability of quartz restricts its use unless the design can be arranged to use only small sections. Aluminum is third but is not as good as granite by a factor of 2. Meehanite, steel, and magnesium are all about the same, but are not as good as aluminum by a factor of 2.

11. Additional Work.

Further data on damping, ductility, and dimensional stability will be obtained and presented in a later report. The numerical effect of material properties on submicron measuring will be investigated and the design approach necessary to maximize the advantages of the materials will be considered.

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Summary of Tabulation of Physical and Metallurgical Properties of Six Materials Ranked in Order of Their Desirability for a Submicron Measuring Machine

| 1. Modulus of Elasticity (Stiffness) E | 2. Density (Weight) | 3. Stiffness/Weight $E/\rho$ | 4. Thermal Conductivity |
|---|---|---|---|
| $10^6$ psi | lbs/in.$^3$ | $10^6$ inches | cal/sec/cm/cm$^2$/°C. |
| 1. Steel 29.0 | 1. Magnesium .064 | 1. Steel 102 | 1. Aluminum .25 to .30 |
| 2. Meehanite 23.0 to 17.5 | 2. Quartz .079 | 1. Aluminum 102 | 2. Magnesium .18 |
| 3. Granite 13.6 to 8.4 | 3. Aluminum .101 | 1. Magnesium 102 | 3. Steel .15 |
| 4. Aluminum 10.3 | 4. Granite .110 | 1. Granite 77 to 123 | 4. Meehanite .14 |
| 5. Magnesium 6.5 | 5. Meehanite .257 | 2. Meehanite 68 to 89 | 5. Quartz .03 |
| 6. Quartz 4.4 | 6 Steel .283 | 3. Quartz 56 | 6. Granite .005 |

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Summary of Tabulation of Physical and Metallurgical Properties of Six Materials Ranked in Order of Their Desirability for a Submicron Measuring Machine

| 5. | Thermal Coefficient of Linear Expansion | | 6. | Thermal Capacity | | 7. | Ratio Thermal Expansion/ Thermal Capacity | |
|---|---|---|---|---|---|---|---|---|
| | $10^{-6}$ in./in./$^{\circ}$C. | | | cal/gram | | | $10^{-6}$ in./in./cal | |
| 1. | Quartz | 0.5 | 1. | Magnesium | .246 | 1. | Quartz | 2.7 |
| 2. | Granite | 5.4 | 2. | Aluminum | .214 | 2. | Granite | 31.4 |
| 3. | Aluminum | 12.0 | 3. | Quartz | .188 | 3. | Aluminum | 56.0 |
| 3. | Steel | 12.0 | 4. | Granite | .172 | 4. | Meehanite | 100.9 |
| 4. | Meehanite | 12.0 to 12.4 | 5. | Meehanite | .119 | 5. | Steel | 104.2 |
| 5. | Magnesium | 26.8 | 6. | Steel | .115 | 6. | Magnesium | 109.0 |

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April 30, 1965

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2nd Preliminary Technical Report

Item 1. Submicron Measurement Error Analysis

Item 1 Work Statement: Evaluate the physical and metallurgical properties of materials used in measuring engine construction to determine comparative suitability to submicron measuring. Materials to be considered are: Meehanite, steel, granite, aluminum, magnesium, and glass.

Submitted by:

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2nd Preliminary Technical Report

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## 1. Summary

In the first preliminary technical report, dated November 9, 1964, certain physical and metallurgical properties were examined to determine which of the following materials are best suited to measuring engine construction:

(1) Meehanite cast iron
(2) Structural steel
(3) Black granite
(4) Aluminum tooling plate
(5) Magnesium tooling plate
(6) Fuzed quartz glass

In subsequent study it was observed that beryllium had properties superior to steel and that certain special glasses had zero thermal expansion. It was therefore decided to include <u>beryllium metal</u> and <u>Cer-Vit C-100</u> glass in the evaluation. Dimensional stability was the principal criterion and the thermal stability and structural rigidity of the materials were considered. The order of preference was found to be:

| a) Thermal dimensional stability | Rank Index* |
|---|---|
| (1) Cer-Vit C-100 glass | 0.00 (ideal) |
| (2) Quartz | 0.10 |
| (3) Beryllium | 1.00 |
| (4) Granite | 1.16 |
| (5) Aluminum | 2.08 |
| (6) Meehanite | 3.74 |
| (7) Steel | 3.86 |
| (8) Magnesium | 4.04 (least desirable) |

| b) Structural rigidity per unit weight | Rank Index* |
|---|---|
| (1) Beryllium | 1.00 (most desirable) |
| (2) Cer-Vit C-100 glass | 4.48 |
| (3) Steel, aluminum, and magnesium | 6.23 |
| (4) Granite | 8.26 to 5.17 |
| (5) Meehanite | 9.35 to 7.15 |
| (6) Quartz | 11.35 (least desirable) |

| c) Structural rigidity under external loads | Rank Index* |
|---|---|
| (1) Beryllium | 1.00 (most desirable) |
| (2) Steel | 1.45 |
| (3) Meehanite | 1.83 to 2.40 |
| (4) Cer-Vit C-100 | 3.13 |
| (5) Aluminum | 4.07 |
| (6) Magnesium | 6.46 |
| (7) Quartz | 9.55 (least desirable) |

*Rank index is based on beryllium = 1.00 with larger values indicating reduced effectiveness.

d) Materials cost

| | | Rank Index* |
|---|---|---|
| (1) | Steel | .0014 |
| (2) | Granite | .004 |
| (3) | Meehanite | .006 |
| (4) | Aluminum | .012 |
| (5) | Magnesium | .016 |
| (6) | Cer-Vit C-100 | .2 |
| (7) | Quartz | .229 |
| (8) | Beryllium | 1.0 |

Thermal dimensional stability is of prime importance since heat sources such as motors, lamps and operators introduce continuously varying thermal conditions. Structural rigidity per unit weight is generally of more importance than structural rigidity under external loads since a design for maximum rigidity will have inherently low stresses and in a measuring engine, the external loads will generally be low.

It has become apparent in the course of the study that two additional characteristics need to be considered:

a. Vibration characteristics of structures

b. Methods of minimizing elastic and plastic deformation of structures.

These characteristics may in some cases be of greater importance than the intrinsic properties of the materials. It is proposed that the study be extended to consider the two additional characteristics.

2. High Modulus of Elasticity Material

Beryllium is a light weight metal of high rigidity. It is well suited to applications requiring high structural rigidity per unit weight. It is stiffer than steel and as light as magnesium. Special precautions must be taken in machining the material due to the toxicity of the dust. Fabrication is generally more expensive than other metals. Ultimate strength and yield strength are similar to structural steel but it is more brittle.

Properties of Beryllium

| | | | |
|---|---|---|---|
| 1. | Modulus of elasticity | 42 | $x10^6$ psi |
| 2. | Density | .066 | lbs/in.$^3$ |
| 3. | Stiffness to density ratio | 636 | $x10^6$ in. |

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| | | | |
|---|---|---|---|
| 4. | Thermal conductivity | .385 | $cal/sec/cm/cm^2/^{o}C.$ |
| 5. | Thermal coeeficient of linear expansion | 13.3 | $x10^{-6}$ in./in./$^{o}$C. |
| 6. | Thermal capacity | .43 to .52 | cal/gram/$^{o}$C. |
| 7. | Ratio thermal expansion/ thermal capacity | 31 to 25.6 | $x10^{-6}$ in./in./cal |

The thermal dimensional stability of beryllium is much better than all the other metals and is slightly better than granite. It is not as good as quartz. The structural rigidity per unit weight is much better than any of the other materials and is in fact six times better than the other metals. The structural rigidity under external loads is better than any of the other materials.

Beryllium metal has properties which indicate it is highly desirable for measuring engine applications. The material cost and fabrication cost will probably restrict its use to critical parts. Since beryllium hot pressed blocks or castings can be ground and polished flat, it would, except for cost, be a good replacement for the present granite and cast iron base blocks. Cost is approximately $70 per pound and may run as high as $100 per pound.

3. Cer-Vit Crystalline Glasses

Cer-Vit is a series of vitreous ceramic glasses with a partially crystalline structure made by Owens-Illinois at their technical center in Toledo, Ohio. The composition of particular interest is the C-100 formulation which has a zero coefficient of thermal expansion.

I believe that Cer-Vit is compounded of a silicate mineral such as petalite or spodumene made by Foote Mineral Company of Epton, Pennsylvania. The minerals are sold by the ton and cost about 6¢ per pound.

Certain of these minerals have negative coefficients of thermal expansion. By selection of percentage of constituents of positive and of negative coefficients of thermal expansion, a material can be compounded with zero coefficient of thermal expansion. Owens-Illinois does not say of what Cer-Vit is made nor do they have a standard product price list. It initially will cost slightly less than fuzed quartz. Eventually they expect it will cost only slightly more than BSC optical glass.

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## Properties of Cer-Vit C-100

| | | | |
|---|---|---|---|
| 1. | Modulus of elasticity | 13.3 | $x10^6$ psi |
| 2. | Density | .091 | $lbs/in.^3$ |
| 3. | Stiffness to density ratio | 147 | $x10^6$ in. |
| 4. | Thermal conductivity | Not Available | |
| 5. | Thermal coefficient of linear expansion | 0 | $x10^{-6}$ in./in./$^{o}$C. |
| 6. | Thermal capacity | .196 | cal/gram |
| 7. | Ratio thermal expansion/ thermal capacity | 0 | in./in./cal |

Note that Cer-Vit C-100 is slightly more rigid and slightly lighter weight than aluminum.

The thermal dimensional stability of Cer-Vit C-100 is better than any of the other materials. Since the coefficient is zero, it is an ideal material in this respect. The structural rigidity per unit weight is better than any of the materials considered except beryllium metal.

The structural rigidity under external loads is better than granite, aluminum, magnesium and quartz. It is not as good as steel and Meehanite. Fabrication problems of Cer-Vit C-100 are probably similar to quartz and other glasses.

4. Comparative Desirability

A summary tabulation of physical and metallurgical properties of materials including beryllium and Cer-Vit C-100 is presented below, ranked in order of desirability for a submicron measuring machine. (The same information presented in the previous report did not include beryllium and Cer-Vit.) It can be seen from the data that in thermal dimensional stability, Cer-Vit C-100 is ideal and beryllium is better than all other materials except quartz. In structural rigidity per unit weight, both beryllium and Cer-Vit C-100 are better than all the other materials.

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4.1 Modulus of Elasticity — $10^6$ psi

| | | |
|---|---|---|
| a) | Beryllium | 42.0 |
| b) | Steel | 29.0 |
| c) | Meehanite | 17.5 to 23.0 |
| d) | Cer-Vit C-100 | 13.3 |
| e) | Granite | 8.4 to 13.6 |
| f) | Aluminum | 10.3 |
| g) | Magnesium | 6.5 |
| h) | Quartz | 4.4 |

4.2 Density — $lbs/in.^3$

| | | |
|---|---|---|
| a) | Magnesium | .064 |
| b) | Beryllium | .066 |
| c) | Quartz | .079 |
| d) | Cer-Vit C-100 | .091 |
| e) | Aluminum | .101 |
| f) | Granite | .110 |
| g) | Meehanite | .257 |
| h) | Steel | .283 |

4.3 Stiffness/Weight Ratio — $10^6$ in.

| | | |
|---|---|---|
| a) | Beryllium | 636 |
| b) | Cer-Vit C-100 | 142 |
| c) | Steel, aluminum & magnesium | 102 |
| d) | Granite | 77 to 123 |
| e) | Meehanite | 68 to 89 |
| f) | Quartz | 56 |

4.4 Thermal Conductivity — $Cal/sec/cm/cm^2/^\circ C$

| | | |
|---|---|---|
| a) | Beryllium | .38 |
| b) | Aluminum | .25 to .30 |
| c) | Magnesium | .18 |
| d) | Steel | .15 |
| e) | Meehanite | .14 |
| f) | Quartz | .03 |
| g) | Granite | .005 |
| h) | Cer-Vit C-100 | Not stated |

4.5 Thermal Coefficient of Linear Expansion — $10^{-6}$ in./in./$^\circ$C

| | | |
|---|---|---|
| a) | Cer-Vit C-100 | 0.0 |
| b) | Quartz | 0.5 |
| c) | Granite | 5.4 |
| d) | Aluminum | 12.0 |
| e) | Steel | 12.0 |
| f) | Meehanite | 12.0 to 12.4 |
| g) | Beryllium | 13.3 |
| h) | Magnesium | 26.8 |

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4.6 Thermal Capacity

| | Cal/gram |
|---|---|
| a) Beryllium | .43 to .52 |
| b) Magnesium | .246 |
| c) Aluminum | .214 |
| d) Cer-Vit C-100 | .196 |
| e) Quartz | .188 |
| f) Granite | .172 |
| g) Meehanite | .119 |
| h) Steel | .115 |

4.7 Ratio of Thermal Expansion to Thermal Capacity

| | $10^{-6}$ in./in./$^{o}$C per Cal/gram |
|---|---|
| a) Cer-Vit C-100 | 0.0 |
| b) Quartz | 2.7 |
| c) Beryllium | 25.6 to 31.0 |
| d) Granite | 31.4 |
| e) Aluminum | 56.0 |
| f) Meehanite | 100.9 |
| g) Steel | 104.2 |
| h) Magnesium | 109.0 |

## 5. Other Aspects of Dimensional Stability

### 5.1 Aging

There is the possibility that a bar of material may change in dimension due to long-term aging. Changes in dimension can be caused by chemical changes such as corrosion or by the relaxation of internal stresses.

Of the materials under consideration, only magnesium has a significant corrosion problem. It is therefore least desirable from a dimensional stability standpoint.

In 1953 the National Bureau of Standards, in a program* to determine the change in length of their meter bars with age, found that their primary standard platinum-iridium meter bar #27 did not change over a 20-year period. Changes in length of their other meter bars of Invar and of stainless steel varied from 1/10 micron to 2/10 micron per meter per year.

Alcoa has always been concerned about changes in dimension of their aluminum jig plate due to relief of locked-in stresses. They take special precautions in annealing their plate to eliminate internal stresses. Such stresses are principally evidenced as warping of a

*NBS Research Paper 2559 "Calibration of Meter Line Standards of Length at the National Bureau of Standards" by Benjamin S. Page. J. of Res. NBS V54, No. 1, Jan. 55

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surface after making a skin cut on a casting. The aging of cast iron castings for several years has the same effect as annealing.

An 8-inch disk of Cer-Vit material was ground and polished flat to 1/10 fringe by Owens-Illinois. When cut in half the disc did not warp. This would indicate that there were no internal stresses which would cause dimensional changes or aging.

Granite, of course, is a naturally occuring material and is already aged many thousands of years. There seems to be no evidence that removing the surface of a granite block has any skin effect which could cause warping such as occurs in the machining of a metal casting.

Although there is no systematic research data dealing with the very small magnitudes of interest here, it appears that proper annealing will largely eliminate internal stresses and changes in dimension with aging will not be a critically important factor.

## 5.2 Creep and Permanent Deflection

Of perhaps greater concern than aging is creep and permanent deflection under load. Creep is the change in deflection with time under constant load and permanent deflection is the inelastic (plastic) deformation remaining when the load is removed.

Creep is usually associated with elevated temperatures and there is very little information about small magnitudes occurring at room temperature. Inelastic deformation is usually associated with the permanent deflections obtained by stressing a material beyond its yield point. Some permanent inelastic deformation occurs even when the stresses are below the yield point. In fact, the yield point is defined as the stress at which 0.2% permanent deflection occurs. This is equivalent to 2,000 microns permanent set per meter.

The best defense is to use very low stress levels. Stresses should be a small fraction of the yield point. Also, highly elastic materials such as steel and quartz are preferred over the less elastic materials such as aluminum and magnesium.

## 5.3 Vibration

Of equal importance with thermal dimensional stability is the control of vibration. Vibration must be attacked from two standpoints:

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a) Elimination of the source

b) Attenuation of the transmission

Both approaches must be used to obtain a satisfactory result. The importance of the above statement cannot be overemphasized. To eliminate sources of vibration, rotating elements (such as fans and motor rotors) must be dynamically balanced; structural elements must be de-tuned so that the natural frequencies and harmonics thereof will not be coincident with the frequencies of operating elements; reciprocating motions such as occur in vacuum solenoids and dancing rollers should not occur during measurement; high speed gear teeth meshing should be avoided.

To attenuate transmission of vibration there are again two standpoints and both must be used to obtain a satisfactory solution:

a) Structures should be supported on vibration isolators and/or air bearings

b) Structures should be deadened

To deaden a structure, bolted and riveted joints should be used and welded joints avoided. Internally damped materials such as Meehanite and magnesium are preferred over undamped resonant materials such as steel and quartz, however, fabrication techniques are probably more important than the material. Structural beams should be of a laminated type of construction, and hollow tubes or pipes should be filled with a damping foam or sand. (This is a common practice in rocket test stand structures.)

Vibration control is of such extreme importance that I propose that it be considered further and that an attempt be made to specify teolerable levels of generation and attenuation.

## 6. Materials Cost

Normally the basic cost of material is not a major consideration in selection for a precision instrument. Usually the man-hour cost for design and manufacture greatly exceed the raw material cost in limited production. For unusual materials, however, this may not be so; therefore a cost comparison is presented here.

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| Raw Material or Structural Shapes | Approximate Cost Per Pound |
|---|---|
| Mild steel, raw stock unfinished | $ .10 |
| Granite surface plate (surface polished flat) | .28 |
| Meehanite cast iron | .42 |
| Aluminum jig plate | .86 to $0.98 |
| Magnesium jig plate | 1.14 to $1.58 |
| Cer-Vit C-100 | Initially less than fuzed quartz, eventually about $2/lb |
| Fuzed quartz ingots (max size 22" diameter x 3" thick or 18-1/2" diameter x 6" thick) | 16.00 |
| Beryllium ingots | 70.00 to $100.00 |

7. Conclusions

Beryllium metal and Cer-Vit C-100 glass outperform all other materials by a considerable margin. The extremely high cost of beryllium, however, limits its use to only the most critical applications. The developmental status of Cer-Vit C-100 also dictates caution in its use. Structural design approaches may be of greater importance than the intrinsic properties of the materials. It is proposed that the study be extended to include consideration of:

a) Vibration characteristics of structures.

b) Methods of minimizing elastic and plastic deformation of structures.

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[redacted] STAT

June 30, 1965

MAILING ADDRESS:

[redacted] STAT

Task II, Item 1, 3rd Preliminary Technical Report

Item 1. Submicron Measurement Error Analysis

## WORK STATEMENT

> Evaluate the physical and metallurgical properties of materials used in measuring engine construction to determine comparative suitability to submicron measuring. Materials to be considered are: Meehanite, steel, granite, aluminum, magnesium, and glass, and other materials that may be particularly suitable.
>
> Evaluate physical properties and structural concepts appropriate to achievement of vibration levels and structural rigidity compatible with submicron measuring requirements. Evaluate methods of measuring the small vibration levels expected in a high performance structure.

Reports No. 1 and No. 2 dealt with the physical and metallurgical properties of materials. This report, No. 3, deals with structural rigidity and vibration control.

Submitted by:

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Task II, Item 1, 3rd Preliminary Technical Report

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Task II, Item 1, 3rd Preliminary Technical Report

## LIST OF FIGURES



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# 1. SUMMARY

## 1.1 Introduction

This report is intended to provide some guidelines for the preliminary design of a structure for a precision stereo comparator. The general major structural components of a stereo comparator for submicron measurement are:

a. The major base blocks
b. The moving platens
c. The microscope objective lens supports
d. The film drive and roller support structures
e. The microscope eyepiece lens support
f. The operator's work station

The film will be carried on the moving platen therefore inadvertent relative movement between the moving platen and the microscope objective must be avoided. To minimize undesired motion the structure supporting the microscope objective should be rigidly anchored to the base block. It is assumed that the microscope and the operator will remain in a fixed position and the moving platen carrying the film format will move to permit viewing different parts of the format with the microscope.

One advantageous arrangement is to place the operator's work station between the two moving platens (see Fig. 1). Such an arrangement imposes certain restrictions on the machine and its structure. For example, the two base blocks should be independently supported since a structure which would tie the two blocks together with the required stiffness appears to be impractical. The microscope eyepiece must be supported independently from the base blocks. Thus there will be relative movement between the two microscope objectives and between the objectives and the eyepiece. The microscope optics must, therefore, incorporate a pivoted link (similar to a stereo arm) which permits the above relative movements without adversely affecting the image observed by the operator. The relative movement to be accommodated will be small.

An alternate arrangement of major structural components is shown in Fig. 2. This arrangement uses one base block, approximately 6 ft x 6 ft to support both moving platens. It is a much less desirable arrangement for operating ease and efficiency, but it places the microscope optical system in one rigid structural unit. The optical relay path length is approximately 3 ft longer than the first arrangement which minimizes the optical relay path length.

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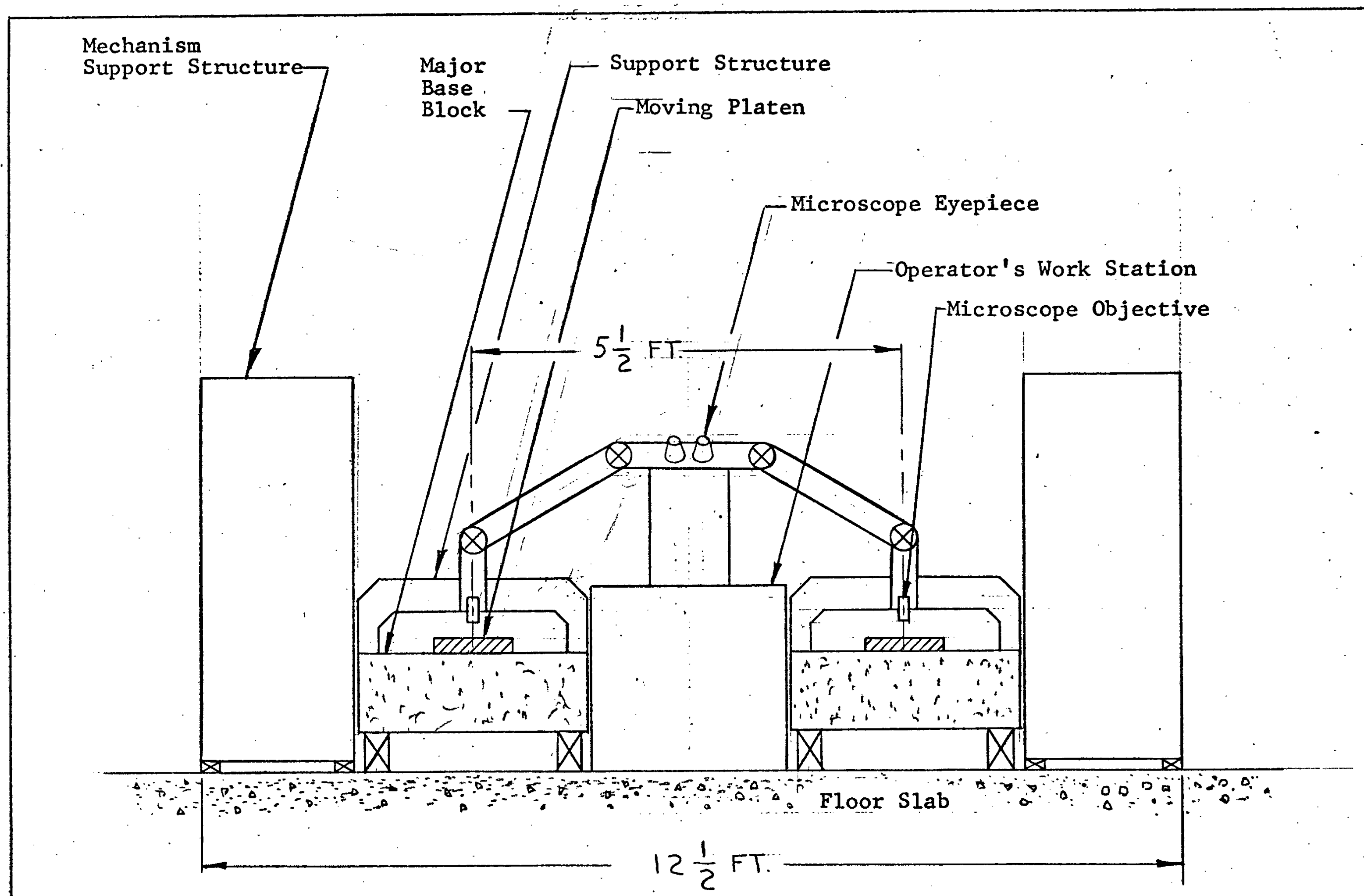


A General Arrangement of Major Structural Components

(Front Elevation View)

Fig. 1

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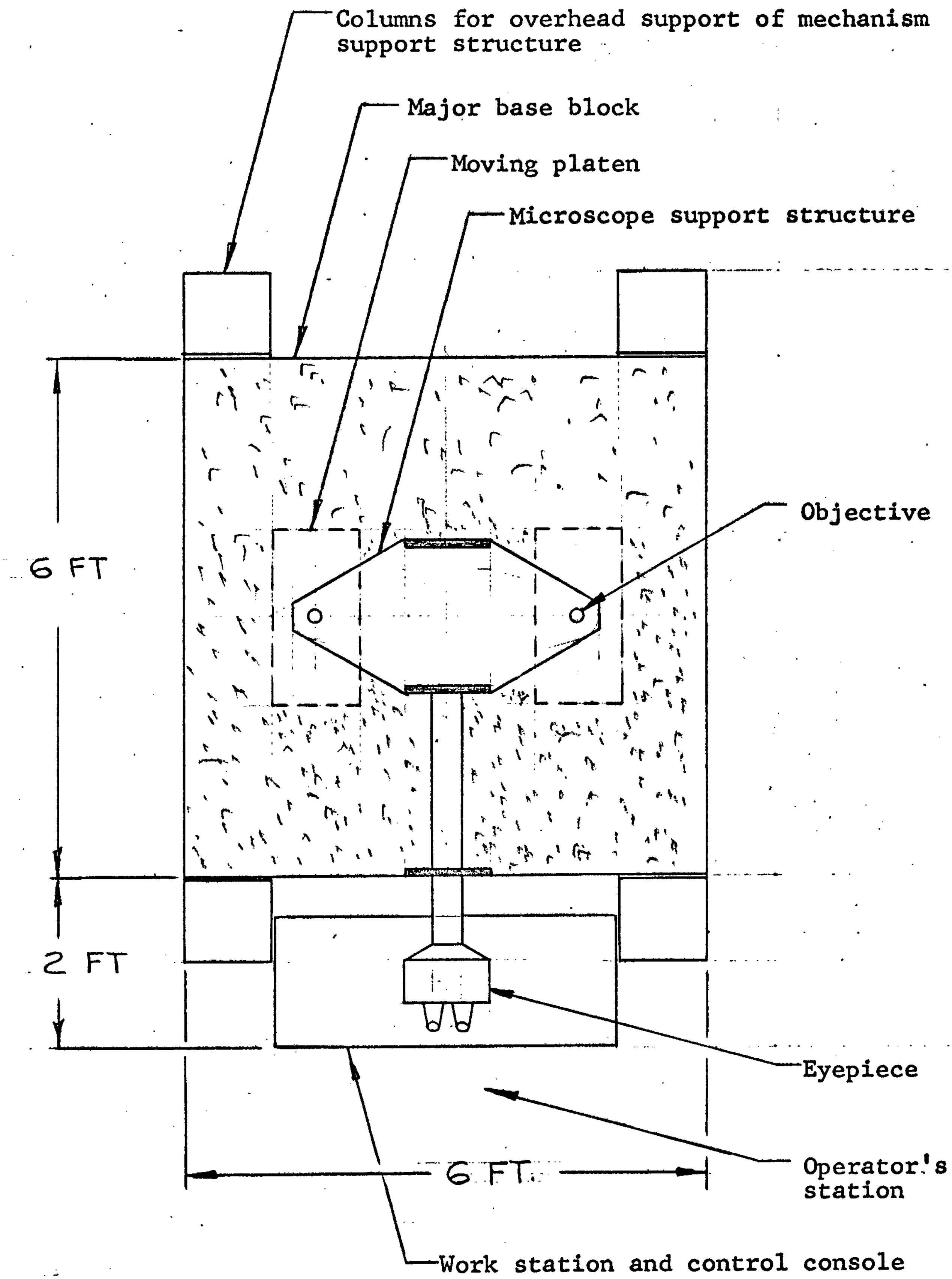


An Alternate General Arrangement of Major Structural Components

(Plan View)

Fig. 2

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Other general considerations of the structure are: (a) the operator's work station must be structurally isolated from the major base block; (b) the mechanism support structure which supports the film rolls and drives, vacuum pump, blowers, etc., must be structurally isolated from the major base blocks; (c) ideally, the natural resonant frequencies of structural components should be widely separated and well damped. Items of concern are:

a. The vibration isolator supports
b. The floor slab
c. The free-free mode of the major base block
d. The free-free mode of the moving platen
e. The moving platen air bearing
f. The microscope objective support structure
g. The microscope eyepiece support structure
h. Every beam, post and bracket in the mechanism support structure
i. The operator's work station

(d) input disturbances should be minimized by dynamic balancing of motor rotors, film rollers, pumps and fans.

A detail analysis of the structural dynamics of the submicron measuring engine can be performed by an existing computer program when the preliminary design of the structure is established. The analysis will provide data for the detail structural design. Section 6 of the report indicates the preliminary design data needed for the computer analysis.

### 1.2 Summary of Report

A homogeneous granite major base block will have a fundamental dynamic frequency of about 410 cps which is satisfactory. Two blocks will weigh about 3400 lbs each. They can be readily supported by the floor with a simple support design.

Cast iron major base blocks will be much more rigid and lighter weight. The fundamental dynamic frequency will be about 765 cps and weight about 2,000 lbs each (including a 2-in. granite cap).

A fabricated steel major base block will be even more rigid. The fundamental dynamic frequency will be 1,710 cps which is excellent. The weight would also be about 2,000 lbs each (including a 2-in. granite cap). Special precautions would be required in the design to insure a well damped structure and to insure that all webs have a high fundamental mode. If the suggested two major base blocks are combined into one, the above weights will double.

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Calculations of the floor slab stiffness indicate it will have a fundamental mode of 20 to 65 cps. It is estimated floor excitation will be between $10^{-2}$g and $10^{-3}$g. The floor slab vibration characteristics should be measured.

The microscope depth of field will be approximately 2 to 8 microns; therefore, the structure which supports the microscope objective lens must be rigidly attached to the major base block. If possible the microscope eyepiece should be independently supported in order to obtain the most effective operating arrangement. The microscope relay lens structure should be vibration isolated so as not to transmit vibration from the eyepiece to the major base block.

The moving platen, if made of 1-1/2-in. thick glass, will have a 120 cps fundamental mode which is too close to the estimated theoretical fundamental mode of 115 cps of the air bearing. A test of the normal transmissibility of the air bearing is needed. Low frequency pressure pulsations in the air bearing should not be allowed to exceed 1% or 2%. The lateral transmissibility of vibration across an air bearing is extremely low. Under worst conditions it should not exceed 1 to 2 millimicrons which is excellent for measuring resolutions of 1/10 micron.

Ideally there should be no mechanical connection between the moving platen and the major base block which could provide a vibration path bypassing the air bearing. Practically, special attention should be paid to minimizing electrical cables, hoses, drive and film loop connections to the moving platen and to designing the required connections for minimum transmission of vibration to the moving platen. Pneumatic and electromagnetic drives should be given special attention for this reason.

The outer structure should house all sources of vibration and shock associated with machine operation. The outer structure should be physically structurally separate from the major base block and the optical support structure. Simple conventional vibration pads are adequate for vibration isolation of the outer structure from the floor. Bolted construction and other damping techniques such as sand filling should be employed. After preliminary design, the elements of the outer structure should be computer analyzed for resonance interactions.

Rotating members of drives, pumps, and blowers should be balanced to achieve a close coincidence of the center of mass to the center of support. Recommended maximum eccentricity versus speed is given.

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Fig. 2a is a composite chart of the vibration frequency data. The chart shows peak-to-peak amplitudes of vibration in microinches vs frequencies at various vibration g levels. The data may serve as design guidelines in sizing the structural components. The actual responses of the structural elements must be calculated by analyzing the structure as a dynamic model.

1.3 Conclusions and Recommendations

The principal conclusions of this report are:

a. A granite major base block will be satisfactory and least expensive. A superior composite steel structure with a granite or glass cap could be designed but would be more expensive.

b. The major base block or blocks should be supported on three pneumatic isolators of about 8 cps natural frequency. Automatic level recovery time should be no more than 2 sec.

c. The principal elastic mode of the floor is estimated to be in the range of 20 to 65 cps and should be measured.

d. The microscope objective lenses should be rigidly fixed to the major base blocks.

e. The microscope eyepiece should, if possible, be separately supported.

f. The operator's work station should be structurally separated from other structure and need not be vibration isolated from the floor.

g. An outer structure should house all machine sources of vibration and shock and should be structurally separate from the major base block. Conventional vibration pads can be used.

h. Air bearings will provide excellent isolation of horizontal vibration. Transmissibility should be well below the 1/10 micron measuring resolution desired.

i. Transmissibility of vertical vibration by the air bearings may have an undesirable characteristic and should be measured.

At this stage recommendations are principally concerned with filling gaps in our information:

a. Measure floor resonance and damping.

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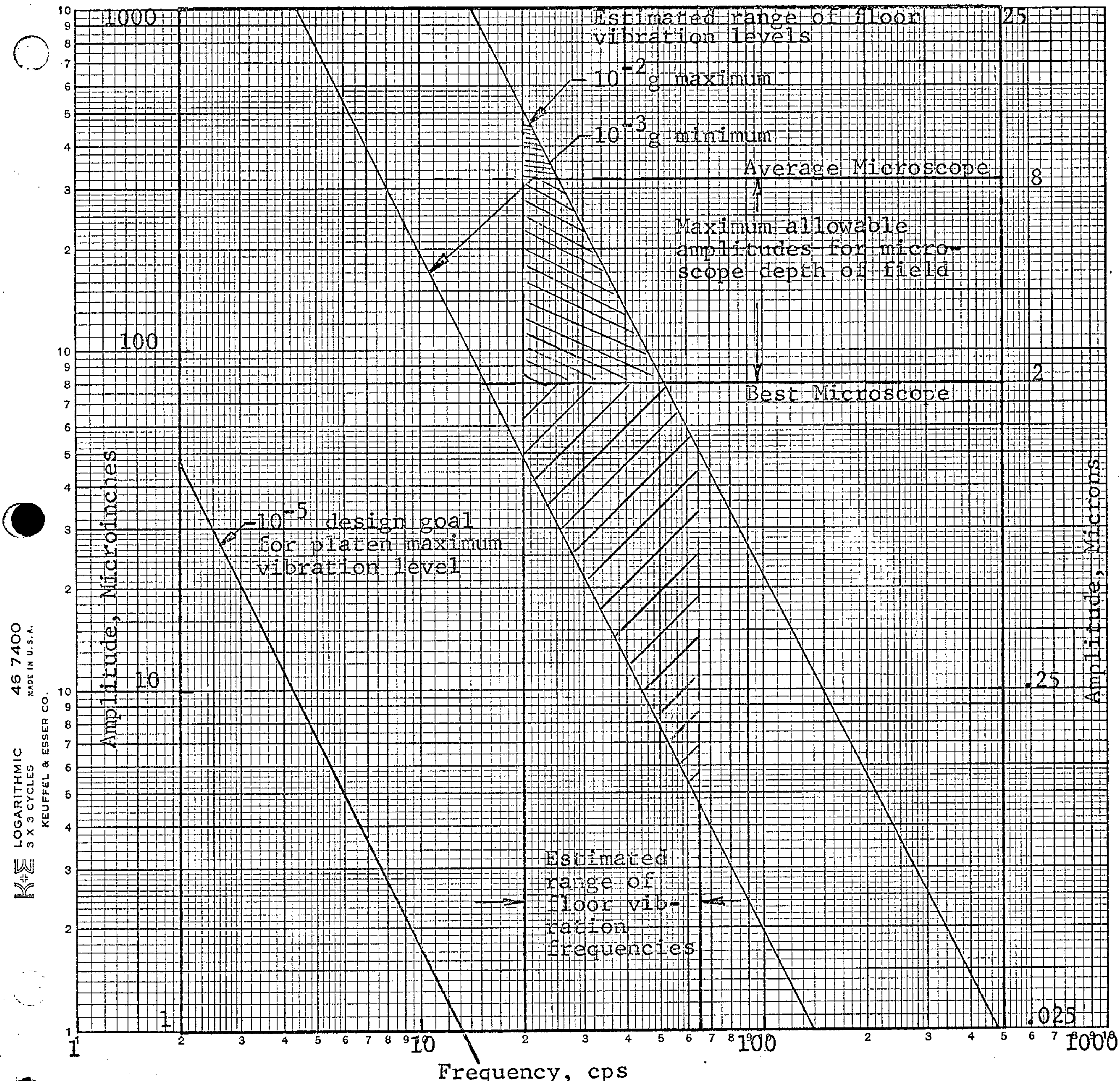


Composite of Vibration Frequency Data

Fig. 2a

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b. Measure natural damping of granite.

c. Measure transmissibility of an air bearing normal to the air cushion.

We suggest that the customer have the above measurements made during the preliminary design phase so that the data will be available for the detail analysis of the structure.

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## 2. THE MAJOR BASE BLOCK

### 2.1 Composite or Homogeneous Construction

The basic structural dynamic requirements of the major base block are as follows:

a. The fundamental bending frequency of the free-free structure should be well above 300 cps.

b. The weight of the block must be such that the loads transmitted through the supports to the floor will not exceed the allowable design loads of the floor.

c. The material and construction of the block should provide high damping to minimize vibration loads.

Three methods of the major block construction have been considered. Each of the methods is described below.

The first construction method is simply a solid granite block (see Fig. 3a) supported by a number of isolators along the fundamental mode node line of the block. This is an homogeneous construction. The surface of the granite can be smoothed and polished. The surface is relatively free of corrosion and easy to keep clean. The material damping of granite is high; however, the flexural rigidity per distributed weight of the homogeneous granite is low compared to cast iron or steel structures. The cost of the homogeneous granite block is lower than other construction methods.

The second method is also a homogeneous construction. The block will be cast to form a waffle-like cast iron structure (see Fig. 3b). With this type of construction the distributed weight, M (lb/in.), along the length dimension is lower than granite. Assuming an 18-in. depth block, the EI/M will be somewhat higher than granite which results in higher bending frequency. Cast iron also has good damping characteristics. One of the disadvantages is that the surface would require protection from rust and corrosion. Care must be exercised in sizing the webs such that the natural frequencies of the webs are well above the fundamental block bending frequency.

The third construction is a composite type made of a bolted steel framed structure 18 in. high with a granite or glass top (see Fig. 3c). The steel-framed structure could be of sandwich type. The compartments can be filled with sand to provide damping. A bolted instead of welded structure

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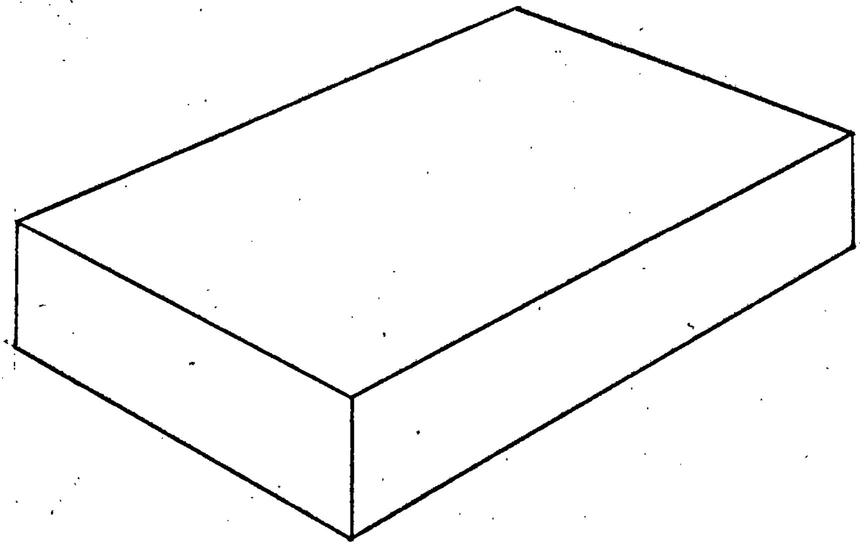
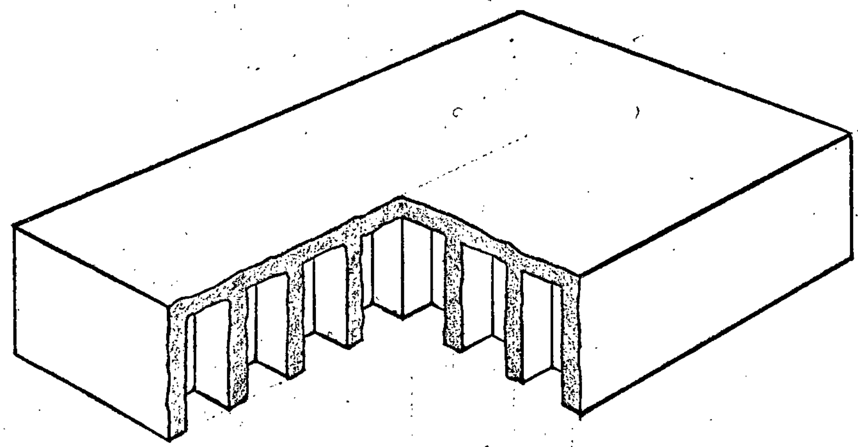
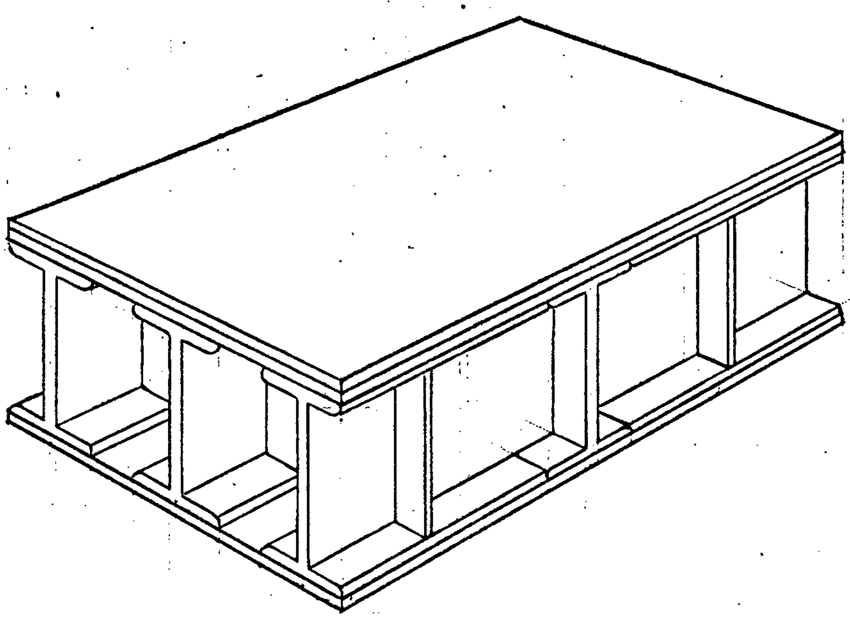


(a) Homogeneous granite block



(b) Cast iron block with waffle pattern bottom



(c) Composite steel block with granite or glass top plate

Major Base Block Construction Fig. 3

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is preferred because of higher structural damping. Of the methods considered, the composite type of construction generally will yield highest EI/M. The total weight of the block is also the lowest.

## 2.2 Weight and Rigidity

As stated in 2.1 the weight requirement of the block is that the support load should not exceed the allowable floor load. Since the support is of point load nature and the floor is of concrete slab construction, the punching shear load will be the criterion in calculating the internal stresses of the floor slab. By providing a steel base plate under the support the loading may be considered a distributed load.

Preliminary estimates of weights for the three types of block construction have been made. The granite block would weigh approximately 3400 lbs. The weight of the cast iron or the steel-framed blocks is approximately 2,000 lbs (including a 2-in. thick granite or glass surface plate).

Assuming the moving plate and the associated equipment would weigh around 200 lbs, the gross weight to floor for the granite block (worst case) will not exceed 3,600 lbs which will be distributed among three supports. If one of the supports receives 1,800 lbs and the support base is 10 in. in diameter, the shear load along the perimeter would not exceed 60 lbs/in. Assuming the support rests on a 10-in. concrete slab, the concrete shear stress would be 6 $lbs/in.^2$ which is well within the allowable.

## 2.3 Principal Elastic Mode of Vibration

The fundamental free-free bending frequenicies of the three block structures have been calculated and listed below:

| Block Type | M(lbs/ft) | $EI(in.^2/lb)$ | f(cps) |
|---|---|---|---|
| Granite | 570 | $2 \times 10^{10}$ | 410 |
| Cast Iron | 330 | $4 \times 10^{10}$ | 765 |
| Steel-framed | 330 | $20 \times 10^{10}$ | 1710 |

The calculations were based on 6 ft-span free-free beams.

## 2.4 Vibration Isolation of the Blocks

To minimize floor excitations to the major base block,

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it is desirable to support the block on isolators.

The mass-spring resonance frequency of the isolators should be well below the fundamental mode of the floor slab. It is undesirable that the isolators be too soft since the moving platen would then cause tilt of the base block. If the moving platen is 10% of the weight of the base block, the tilt could be as much as 10% of the static deflection of the isolators. To eliminate permanent tilt of the major base block, a self-leveling pneumatic type isolator such as the Barry Controls SERVA-LEVL should be used. The very soft standard 2 cps SERVA-LEVL has a level recovery time of 15 to 20 sec which is too long. To prevent interaction of the level recovery system and the vibration isolation action the level recovery time constant must be long compared to the vibration isolator time constant. Probably an 8 cps mount with a 1 to 2 sec level recovery time would be a good compromise.

2.5 Interaction with the Floor Slab

In general, if the floor structure is of reinforced concrete construction, the fundamental bending frequency will be above 15 cps. A preliminary estimate of the bending frequency of the floor where the submicron measuring system will be located is somewhere between 20 and 65 cps.

The criteria set forth in 2.1 and 2.4 were generated from the knowledge of the floor structure.

The relative displacement transmissibilities considering a system indicated in Fig. 6a can be expressed by the following equation:

$$\frac{X_3}{X_1} = \sqrt{\frac{\left[\left(2\zeta_1 \frac{\omega_F}{\omega_A}\right)^2 + 1\right]\left[\left(2\zeta_2 \frac{\omega_F}{\omega_B}\right)^2 + 1\right]}{\left\{\left[1-\left(\frac{\omega_F}{\omega_A}\right)^2\right]^2 + \left(2\zeta_1 \frac{\omega_F}{\omega_A}\right)^2\right\}\left\{\left[1-\left(\frac{\omega_A}{\omega_B}\right)^2\right]^2 + \left(2\zeta_2 \frac{\omega_F}{\omega_B}\right)^2\right\}}}$$

where

$\omega_A$ = Floor excitation resonant frequency

$\omega_B$ = Isolation system frequency

$\omega_F$ = Major base block resonant frequency

$\zeta_1$ = Damping ratio of the isolation system

$\zeta_2$ = Damping ratio of the base block

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Sections 6 and 7 will discuss further analytical and experimental work to determine the over-all structural dynamic performance of the submicron measuring system. The floor excitations and interaction with the measuring system are of major consideration.

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## 3. THE MICROSCOPE OBJECTIVE SUPPORT

### 3.1 Microscope Depth of Field

The allowable relative movement of the film platen and the microscope objective support is governed by the microscope depth of field.

$$DF = \frac{\lambda \sqrt{n^2 - (NA)^2}}{(NA)^2}$$

where

$\lambda$ = Wave length of light = $0.5 \times 10^{-6}$ meters

n = Index of refraction of air = 1

NA = Numerical aperture which varies from 0.25 to 0.5

The DF range varies from 80 to 320 microinches (2 to 8 microns).

### 3.2 Some Structure Criteria

The microscope objective support structure criteria are:

a. The resonant frequency should be at least twice that of the major base block.

b. The relative peak-to-peak movement should be less than 80 microinches (2 microns) under any excitations.

c. The optical linkage components connecting the eyepieces should not transmit appreciable vibration load to the microscope objective structure.

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# 4. THE MOVING PLATEN

## 4.1 General Size and Construction Considerations

The required observable format size for each platen is 10 in. x 20 in. The glass plate can therefore be assumed to be approximately 1 ft x 2 ft. To obtain adequate flatness (approaching an optical flat) it will need to be at least 1 in. thick and may need to be 2 in. thick. The weight of the plate only will, therefore, be from 25 to 50 lbs. Additional thickness will be required for vacuum slots. In addition, structure will be required for supporting the glass plate, for air bearings, for the ways, for the X-axis measuring engine, for the intermediate ways and for the Y-axis measuring engine. The total weight will probably not exceed 200 lbs for each moving platen of the stereo pair.

## 4.2 Air Bearing Normal Transmissibility and Pulsation

The air bearings which will support the moving platen on the base blocks will help to isolate the platen from vibrations in the base. The air bearing will act as a damped spring and with the supported mass will have a frequency response characteristic dependent on the spring-mass constants. Amplification at the resonant frequency will depend upon the damping. As a first approximation of transmissibility we assumed the air bearing would follow the same principles as an air bearing isolator in which the natural resonant frequency is determined by the air column height. The air column height was assumed to be the thickness of the air cushion in the air bearing. The resonant frequency is therefore estimated to be:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{g\,\gamma}{y}}$$

where

$f_n$ = Resonant frequency, cps

$g$ = Gravity constant = 386 in./sec$^2$

$\gamma$ = Ratio of specific heats of air = 1.4

$y$ = Thickness of air cushion = 0.002 in. (assumed)

thus

$$f_n = \frac{1}{2\pi}\sqrt{\frac{386\ (1.4)}{0.002}} = 82.5 \text{ cps}$$

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The curve of Fig. 4 illustrates the estimated theoretical transmissibility of the air bearing. Note that below 25 cps a 0.002-in. thick air bearing will transmit vibration at 1:1. Between 25 cps and 150 cps an 0.002 -in. thick air bearing will amplify vibration as much as 1.4:1. Above 150 cps it attenuates vibration and at 300 cps the transmissibility is 0.3. Transmissibility is defined as the output amplitude divided by the input amplitude.

For an 0.001-in. thick air bearing $f_n$ = 115 cps. The curve will be similar but shifted to the right as shown.

The actual response of an air bearing to vibration inputs may differ appreciably from the estimated theoretical transmissibility shown here. A more realistic theoretical analysis immediately becomes exceedingly complex and no dynamic analysis of an air bearing has been found in the literature. A measurement of the frequency response of a typical air bearing is recommended since it appears that the air bearing will amplify vibration in the frequency range of the floor inputs and at the fundamental mode of the glass platen.

Pressure pulsations in the air bearing, if they are of low frequency, will change the air cushion thickness. If the air cushion is 0.001-in. thick then a 10% pressure variation will cause the platen to move 2-1/2 microns which is unacceptable for the depth of the field of the best microscopes. A 1% pulsation would cause only 1/4 micron movement of the platen which is acceptable.

### 4.3 Air Bearing Lateral Transmissibility and Pulsation

For horizontal vibration the air bearings will be a highly effective isolator. Motion will be transmitted across the bearing by shear in the air cushion. The shear force is given by:

$$F = A\mu\frac{dV}{dy}$$

where

$F$ = Force on supported member, lbs

$A$ = Area of supporting air cushion, $ft^2$

$\mu$ = Viscosity of air = $.04 \times 10^{-5}$ lb sec/$ft^2$

$\frac{dV}{dy}$ = Velocity gradient of the air across the thickness y of the air cushion in ft/sec/in.

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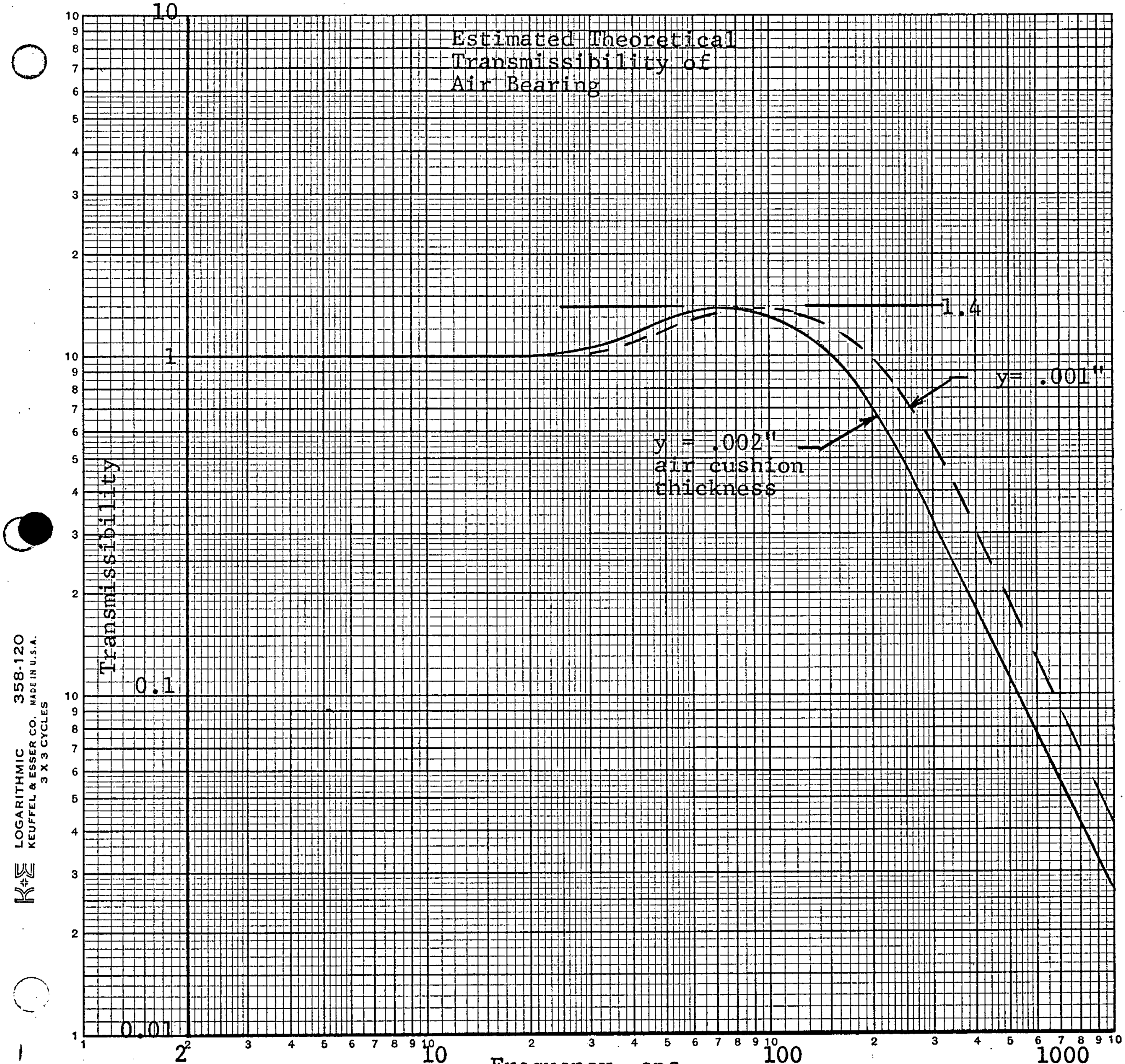


Fig. 4

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By assuming some fairly extreme worst case conditions, we can demonstrate that lateral transmissibility across the air cushion is negligible.

Assume a base vibration of 300 microinch amplitude and about 65 cps (i.e., 400 rad/sec), then peak velocity of the base will be 0.12 in./sec. The force transmitted to the supported member will be:

$$F = \frac{40}{144} \times 0.4 \times 10^{-5} \times \frac{.12}{.001} = 1.33 \times 10^{-3} \text{ lbs}$$

for $A = 40 \text{ in.}^2 = 40/144 \text{ ft}^2$

$\mu = 0.4 \times 10^{-5}$ lb sec/ft$^2$

$dV = 0.12$ in./sec

$dy = 0.001$ in. air cushion thickness

For a 200-lb supported weight this is less than $10^{-5}$g which corresponds to approximately 1-1/2 millimicrons amplitude. Such amplitude is negligible compared to the 1/10 micron resolution desired.

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# 5. THE OUTER STRUCTURE

## 5.1 Some Structure Criteria

The outer structure will support the film drive system and other operating equipment. Although the outer structure will be isolated from the floor and the major block, any excitation of the outer structure to the floor will be transmitted to the major base block. The criteria of the outer structure design are listed below:

a. The resonant frequencies of all the components and their mountings to the outer structure should be well separated from the resonant frequencies of the floor slab, block isolation system, and the first elastic mode of the major base block.

b. Bolted structure is preferred to welded structure for higher structural damping.

## 5.2 Vibration Isolation of the Structure

The purpose of the isolation of outer structure from the floor is to minimize floor excitation. With a proper conventional design of mounting pad the goal can be achieved. It is not necessary to incorporate a pneumatic isolation system as required for the major block. Care must be exercised in designing the isolation mount such that the isolation frequency is not near the floor resonant frequency.

## 5.3 Some Criteria for the Drives, Pumps and Blowers

To minimize the sources of vibration in the outer structure, good balancing of the rotating components of the drives, pumps, and blowers are essential.

The criteria to achieve good balancing are as follows:

a. The permissible unbalance tolerances for these items in terms of millimeter-grams of permissible residual unbalance per kilogram of rotor weight should be in the order of 0.5. This is equivalent to center of gravity displacement of $20 \times 10^{-6}$ in.

b. The bearing displacement versus speed of the rotating equipment should be in the shaded area of Fig.5.

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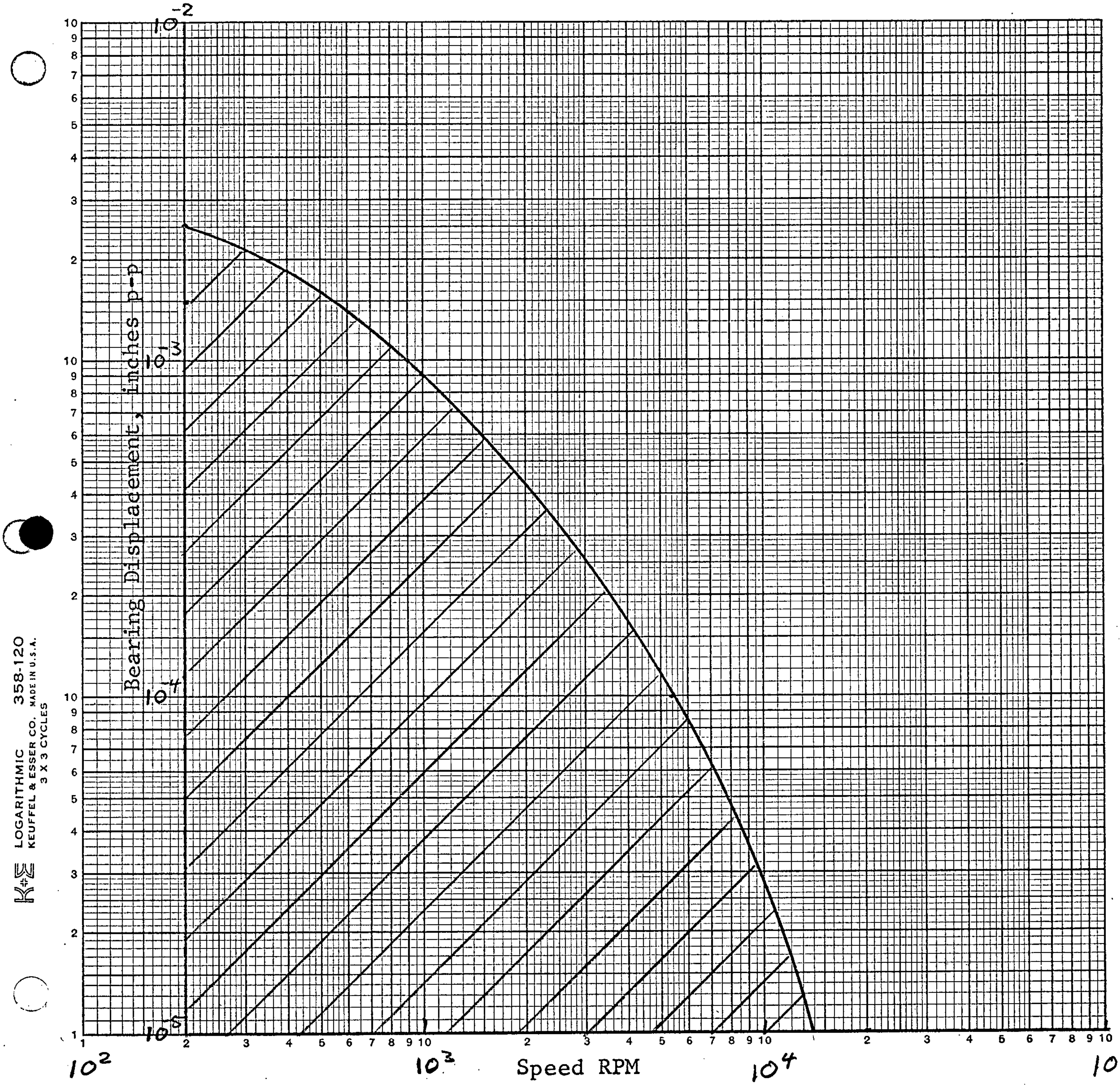


Machinery Vibration Limit for Very Smooth Running

Fig. 5

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# 6. DETAIL ANALYSIS OF THE STRUCTURE FOLLOWING PRELIMINARY DESIGN

## 6.1 Analytical Approach

One of the main factors that affect the performance of the submicron measuring system is the understanding of the structural dynamic behavior of the system.

The dynamic response of the major base block will be of chief concern. Block vibration loads will be transmitted to the moving platen and the measuring system as well as the microscope supports. When the preliminary machine design is established, a detail study of the block structure under floor excitations can be made. Dynamic behavior of other structural and mechanical components can also be analyzed to obtain the over-all performance limits of the submicron measuring system.

An existing IBM 7094 computer routine is available for detail analysis of the structural dynamic responses of the major base block. The capabilities of the routine will be described in 6.2.

The performance of the block isolation system should also be well understood. The pneumatic system is a non-linear system. The stability and response characteristics of the servo-control loop should be simulated by an analog or digital computer.

## 6.2 The Computer Program for Structural Dynamic Analysis

An IBM 7094 computer program named LESAR (Linear Elastic Structural Analysis Routine) has been developed recently by [redacted] A brief description of the routine STAT is given below.

LESAR performs static and dynamic analyses of any linear structure which can be idealized as one of the following frameworks:

Type 1 - Three dimensional pin-jointed framework (examples of structures which can be so idealized--spaceframes, membranes, box beams).

Type 2 - Three dimensional rigid-jointed framework (e.g., spaceframes, shells, box beams, curved beams).

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Type 3 - Two dimensional rigid-jointed framework, loaded in-plane (e.g., bars, curved planar beams, rings, planar frames).

Type 4 - Two dimensional rigid-jointed framework loaded normal-to-plane, also called a two dimensional grid (e.g., plates, planar frames, arches, beams).

A framework is defined as a system of uniform weightless bars connected together at joints to form a stable structure. At the joints, inertias are lumped and loads are applied. The bending, torsional, and axial stiffnesses of the bars simulate the elastic properties of the corresponding structure. The lumped inertias and loads represent the actual distributed inertias and applied forces.

The framework and its environment can be described by the following quantities:

a. Coordinates of joints

b. Geometry and elastic properties of bars connecting the joints

c. Lumped inertias at joints

d. Restraints at joints

e. Loads applied at joints

Given these quantities as input LESAR will perform computations to provide the following output:

1. Stiffness matrix for the structure

2. Up to 12 Eigenvalues and Eigenvectors (modes and frequencies)

3. Response to loading conditions:

   a. Deflections and internal loads (moments, shears, torques, and axial forces) within the structure for static loads.

   b. Time history of deflections and internal loads for transient excitations.

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c. Deflections and internal loads as a function of frequency for harmonic excitation.

4. Summary of the maximum design loads occurring at joints.

The program is versatile as far as the structural types and excitations are concerned. The only limitation is in the total number of degrees of freedom which is 102. For the base block analysis, Type 4 structure will be used. The maximum number of degrees of freedom is not expected to exceed 80.

The use of this routine will provide structural dynamic analysis of the submicron measuring engine structure to a sophisticated degree. Computer time will normally not exceed 5 minutes per set of input conditions.

In the present study, LESAR was used to analyze the free vibration of the floor slab.

In future structural dynamic analysis of the major base block, the block-support system will be organized as a mechanical system as given in Fig. 6a.

Considering vertical motion only, the following data will be generated:

1. Three rigid body frequency modes (1 vertical, 2 rotational with respect to block surface).

2. Up to 9 elastic modes and frequencies.

3. Static and dynamic deflections and stresses to given loading conditions.

Similar models can be established for motion sideways to yield other rigid body modes, but this is not believed necessary. The stiffness of the block in the plane direction is high, and it is not necessary to carry out the elastic motion computation of the block. Knowing the isolation stiffness horizontally, the rigid body modes can be hand computed without resorting to computer routine.

### 6.3 Servo-Control Loop of the Isolation System

The isolation system stiffness requirement will depend on the dynamic behavior of the major base block. The level recovery time requirement of the system will be derived from the following considerations:

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1. The moving platen will be free of oscillations or unstable motions throughout the slew rate range of the measuring engine.

2. Should a two-base-blocks system be chosen, the relative motions of the blocks should be small and the recovery time should be such that the motion disturbances of the eyepieces will be at a practical minimum.

As indicated in 2.4, an 8 cps mount with a 1 to 2 sec. level recovery time may be desirable for the pneumatic isolation system. The position-sensing valve design of SERVA-LEVL would probably not permit the fast response requirements.

In general, a fast response pneumatic system would require an electro-pneumatic controller which actuates a servo valve through error signals received from displacement and/or velocity sensors.

Fig. 6b shows a typical servo-control loop mechanism of the pneumatic isolation system.

Since the pneumatic transfer functions are non-linear, the servo-control system will involve a set of non-linear differential equations relating the parameters $P_1$, $P_2$, $V_1$, $V_2$, $P_{1_T}$, $P_{2_T}$, $P_s$, $A_1$, $A_2$, $X_a$, $X_b$, and the controller transfer function. The solutions of the equations can be programmed for either a digital or analog computer.

The degree of sophistication in the servo-control loop is dependent on the requirements derived after preliminary structural dynamic design of the complete submicron measuring system.

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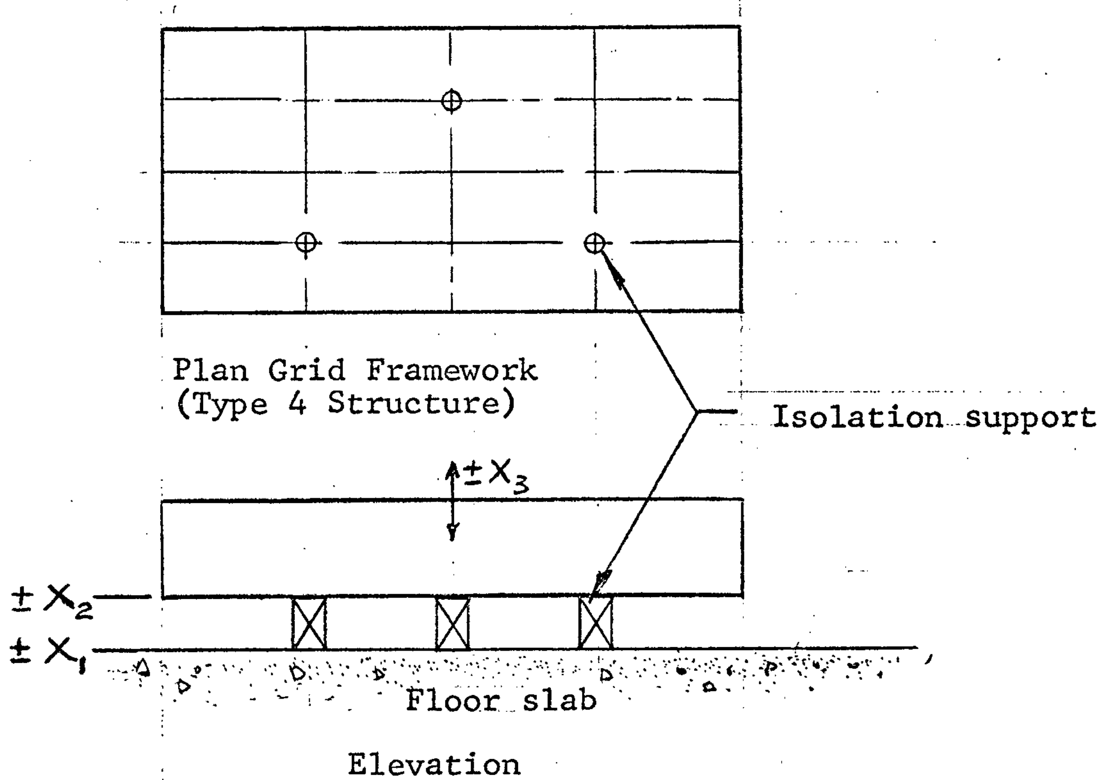
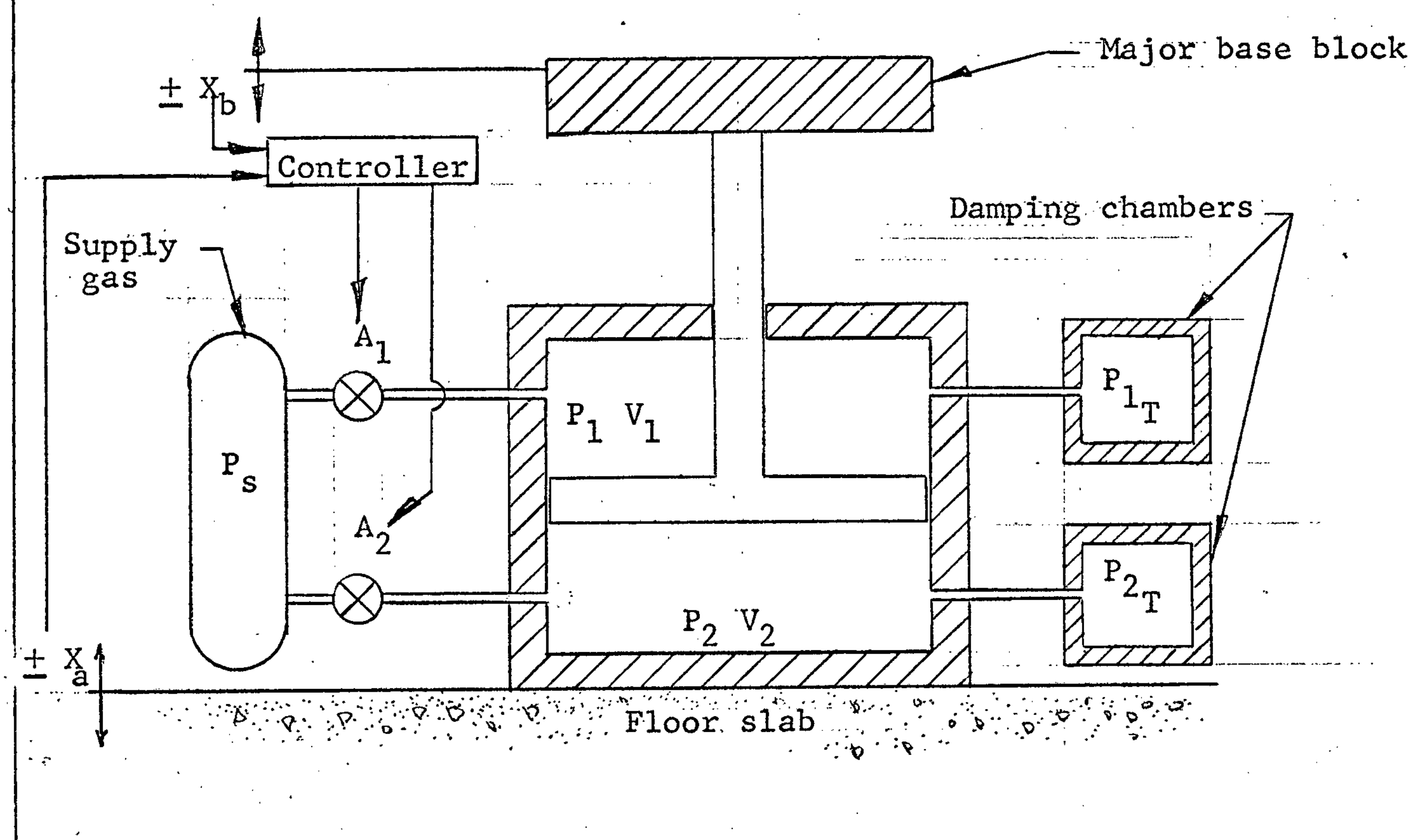



Major Base Block Mechanical System

Fig. 6a




Pneumatic Isolator Servo-Control System

Fig. 6b

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# 7. METHODS OF MEASURING STRUCTURE PERFORMANCE

## 7.1 Floor Dynamic Environmental Data

For detail structural dynamic analysis of the design of the submicron measuring system, the dynamic environmental data of the floor where the system will be located will be needed.

The data of interest are the following:

a. Fundamental resonant frequency
b. Damping characteristics
c. Acceleration environment

These data will be used to determine the isolation requirements of the outer structure and the major base blocks.

The resonant frequency and the damping characteristics of the floor slab can be measured by simply applying a hammer blow (using a lead hammer) and recording of acceleration-time history. In general, the fundamental resonant frequency and the damping ratio can be obtained simultaneously from the acceleration-time history record by measuring the period and calculating the decay rate. However, should the noise level of the floor be higher than the hammer blow or if more than one frequency is excited, the data will be difficult to reduce.

An alternate measuring method is to attach a small vibration exciter (such as an electrodynamic shaker with sweep frequency range of 5 cps to 100 cps) to the floor supplying the excitations. The accelerometer response will again be recorded. At resonant frequency, a survey on adjacent points should be made so that the damping ratio can be determined.

To measure the acceleration environmental condition of the floor a portable acceleration recorder will be employed. The sensitivities of the recorder should be in the order of $10^{-3}$g and $10^{-5}$in. Measurements should be made in all three directions.

## 7.2 Granite Damping Characteristics

Having obtained the floor environmental data, the major block and isolation system design can proceed. One of the factors in choosing the major block construction technique is the damping characteristics of the three types of construction considered.

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Damping data are available for cast iron and steel-framed structures. Research will be needed to obtain the material damping data of the granite. In the event that data are either not existant or not complete, a resonant survey of a specimen granite block should be performed on an electro-dynamic shaker.

The material damping energy is generally a function of internal stresses; thus in performing the resonant survey, the input acceleration level of the shaker should be comparable to the level of floor acceleration environment.

### 7.3 Tests of Critical Items

It may be necessary to perform vibration level tests on critical items of the submicron measuring system for the following reasons:

a. Items which are either moving parts (rotors, fans, etc.) or parts transmitting motions (gear, linkage, etc.) will generate vibration sources. These parts must be properly balanced or tested to be sure that the frequencies are well separated from other major items of the system.

b. Items which directly affect the measurements of the film coordinates (measuring engine, moving platen, etc.) should also be tested to insure structural integrity.

Specific determination of which items are critical can be made during preliminary design of the submicron measuring instrument.

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# APPENDIX

## Free Vibration Analysis of 20'x20' Floor Slab by IBM 7094 Computer Program

The floor structure is made of a non-uniform two dimensional plate. Hand calculations of the modes and frequencies will be laborious and inaccurate. A computer analysis of the free vibration of the 20'x20 concrete floor slab has been carried out.

In this Appendix section we shall be concerned with the structural dynamic model of the floor slab. In a subsequent report, the input/output of the computer run and the results of the computation will be discussed.

Figure 7a shows the grid framework of the floor slab. Figure 7b shows a cross section of the floor slab.

A number of assumptions of the floor slab model are given below:

(1) The effective depth of the members adjacent to the columns is 32".

(2) The effective depth of the remaining members is 8".

(3) The concrete strength is 2000 psi which results in $E_c$= 2,000,000 psi.

(4) The distributed weight of the slab is 125 psf.

(5) Members 3-26, 11-27, 15-28, and 23-29 in Figure 7a are dummy members simulating the stiffness of the adjacent floor bays. Joints 1, 5, 21, 26, 27, 28, and 29 are restrained in all directions.

The input data will then be organized based on the model. The input and output data of the LESAR run will be tabulated in the future report.

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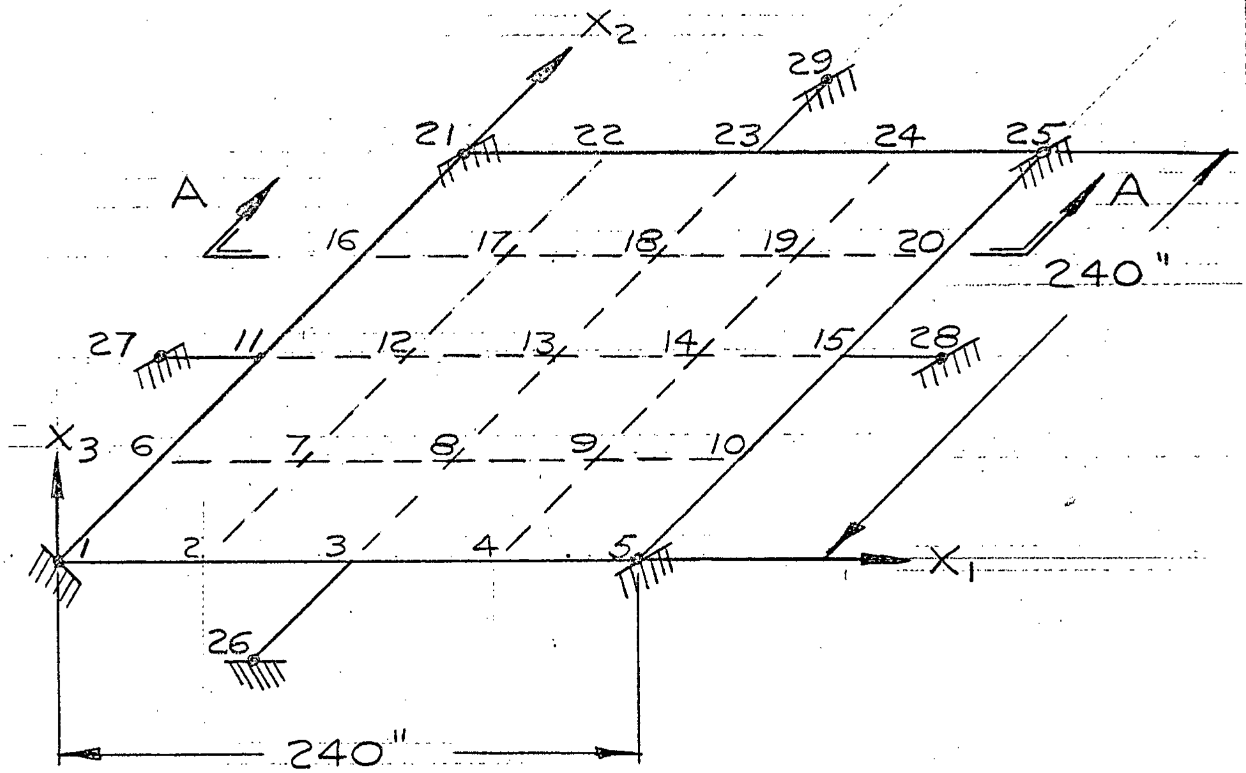


Figure 7a    Floor Slab Grid Framework

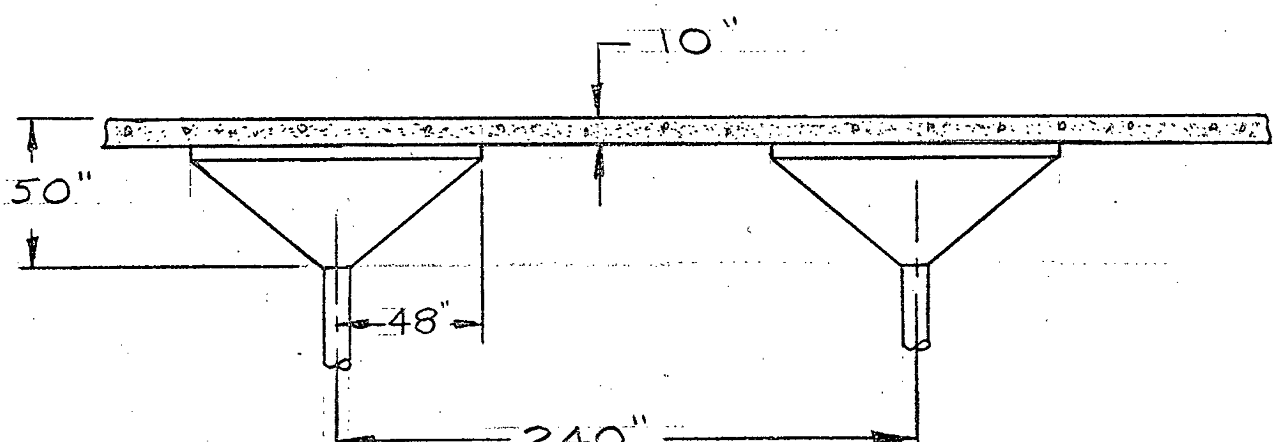


Figure 7b    Section A-A of Floor Slab

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July 30, 1965

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Task II, Item 1, 4th Preliminary Technical Report

Item 1. Submicron Measurement Error Analysis

WORK STATEMENT

> Evaluate the physical and metallurgical properties of materials used in measuring engine construction to determine comparative suitability to submicron measuring. Materials to be considered are: Meehanite, steel, granite, aluminum, magnesium, and glass, and other materials that may be particularly suitable.
>
> Evaluate physical properties and structural concepts appropriate to achievement of vibration levels and structural rigidity compatible with submicron measuring requirements. Evaluate methods of measuring the small vibration levels expected in a high performance structure.

Reports No. 1 and No. 2 dealt with the physical and metallurgical properties of materials. Report No. 3 dealt with structural rigidity and vibration control of the machine structure. This report, No. 4, presents results of a computer analysis of building floor vibration frequency.

Submitted by:

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Task II, Item 1, 4th Preliminary Technical Report

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## 1. SUMMARY

A free vibration analysis of one typical bay of an upper story floor of a building has been made. The floor is a multiple bay slab-column structure. The purpose of the analysis was to determine the fundamental and higher mode frequencies of the floor slab. Knowledge of the floor frequencies is important to determine the interaction of floor with the vibration isolation system of a projected submicron measuring machine.

The assumed floor structural dynamic model is shown in Figure 1a and 1b. The analysis was carried out by an existing IBM 7094 routine. The result of the computation indicates the fundamental frequency is 15.6 cycles per second. If the data on the floor construction is accurate the analysis will yield a 10% accurate fundamental frequency. The fundamental frequency may therefore vary from 14 to 17 cps. The computed 15.6 cps. fundamental floor frequency is much lower than the 20 cps. to 65 cps. anticipated in report No. 3. If the floor frequency is that low, it would necessitate a machine vibration isolator system of much lower natural frequency than the 8 cps. suggested in report No. 3.

Before proceding further on the structure evaluation, the floor frequencies will be reexamined with more accurate data on the floor construction.

## 2. STRUCTURAL DYNAMIC MODEL OF THE FLOOR SLAB

Figure 1a shows the grid framework of the floor slab.

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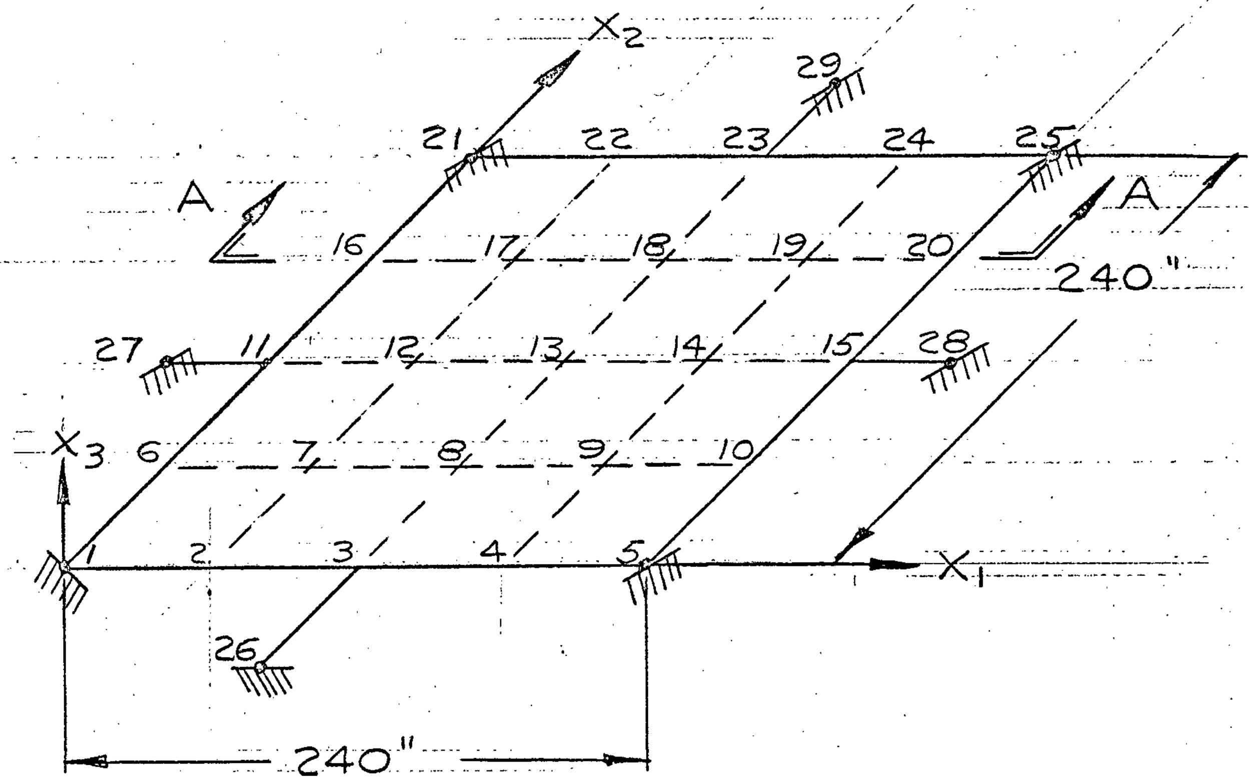


Figure 1a Floor Slab Grid Framework

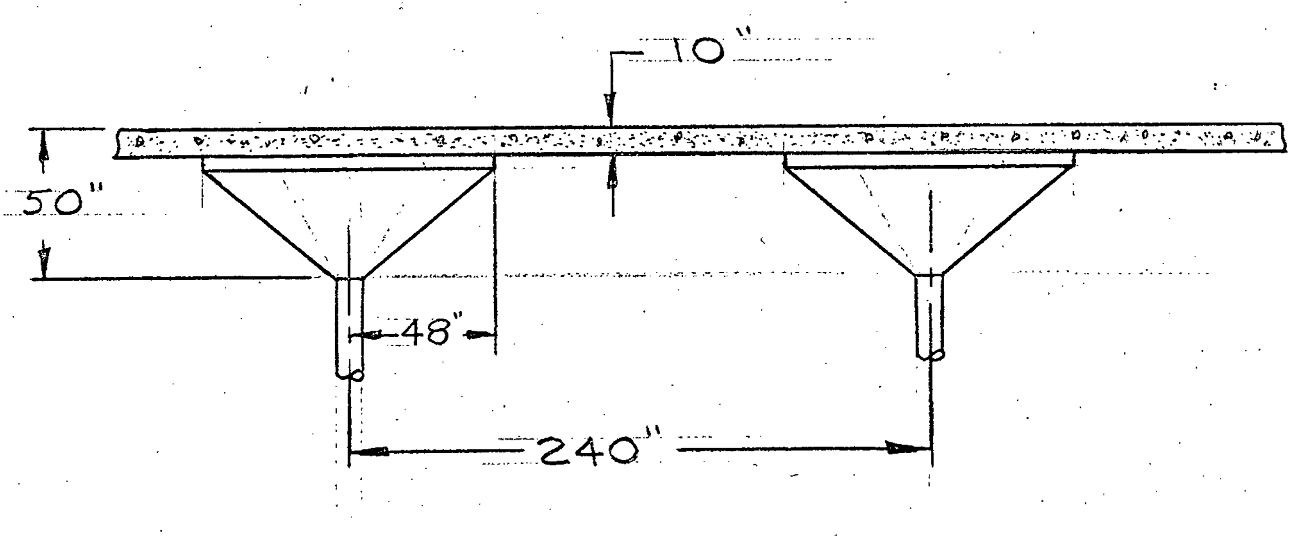


Figure 1b Section A-A of Floor Slab

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Figure 1b shows a cross section of the floor slab.

The assumptions of the floor slab model are:

(1) The effective depth of the members adjacent to the columns is 32 inches.

(2) The effective depth (top fiber to the center of reinforcing rod) of the remaining members is 8 inches.

(3) The concrete strength is 2000 psi which results in Ec=2,000,000 psi.

(4) The distributed concrete dead weight of the slab is 125 psf.

(5) Members 3-26, 11-27, 15-28, and 23-29 in Figure 1a are dummy members simulating the stiffness of the adjacent floor bays. Joints 1, 5, 21, 26, 27, 28, and 29 are restrained in all directions.

## 3. INPUT DATA

Table I lists the inputs data to the existing computer program, LESAR, for the free vibration analysis of the 20'x20' concrete floor slab. The quantities are as follows

(1) Joint Coordinates
There are three columns, joint number, XI and X2 coordinates in inches.

(2) Member Properties
The first two columns indicate the ends of members. A(3) and A(4) are width and depth of members. The effective moment of inertia and torisional rigidity of each member will be computed by the input width and depth.

(3) Restraints
Those joints that are restrained are shown.

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## 4. OUTPUT DATA

Table II lists the modes and frequencies computed for the floor slab. Six frequencies and the corresponding mode shapes are given for this run. In the mode shape columns, there are three quantities associated with each joint. The first of these numbers is the dimensionless deflection in X3 direction. The second and third numbers are rotational modes in X1 and X2 dirctions. All these quantities are normalized so that the maximun is equal to unity. The modes corresponding to X3 deflection are of interest. Figure 2 shows the fundamental mode shape of the floor slab.

## 5. DISCUSSION OF RESULTS

The fundamental frequency of the floor slab obtained from the computer run is 15.578 cps. This floor diaphram frequency is low and considered critical as far as the effect to the overall accuracy of the submicron measuring system is concerned.

Since the computation was based on the assumed structural dynamic floor model, the result should not be considered final. Further analysis should be performed to confirm the data.

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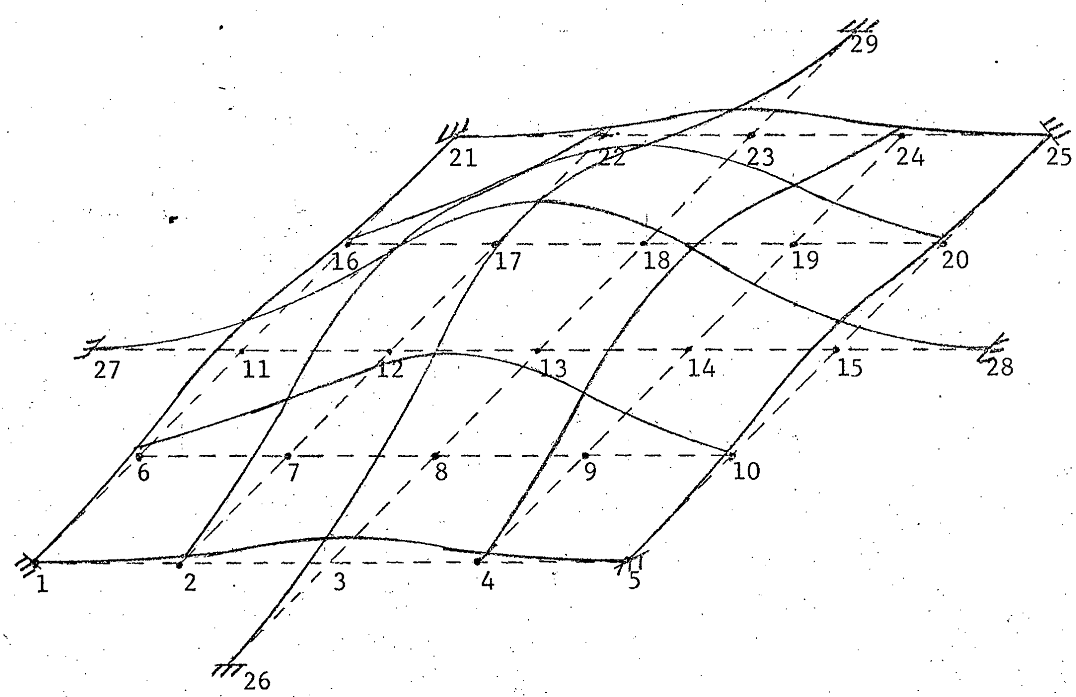


Figure 2 Fundamental Mode Shape of the 20' x 20' Concrete Floor Slab

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TABLE I

CONCRETE FLOOR FREE VIBRATION ANALYSIS (TYPE 4 GRID STRUCTURE)
20 FEETX20 FEET BAY,6 MODES REQUIRED, [redacted]

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INPUT DATA

JOINT COORDINATES

| JOINT | X(1) | X(2) | X(3) |
|---|---|---|---|
| 1 | 0. | 0. | -0. |
| 2 | 60.00000 | 0. | -0. |
| 3 | 120.00000 | 0. | -0. |
| 4 | 180.00000 | 0. | -0. |
| 5 | 240.00000 | 0. | -0. |
| 6 | 0. | 60.00000 | -0. |
| 7 | 60.00000 | 60.00000 | -0. |
| 8 | 120.00000 | 60.00000 | -0. |
| 9 | 180.00000 | 60.00000 | -0. |
| 10 | 240.00000 | 60.00000 | -0. |
| 11 | 0. | 120.00000 | -0. |
| 12 | 60.00000 | 120.00000 | -0. |
| 13 | 120.00000 | 120.00000 | -0. |
| 14 | 180.00000 | 120.00000 | -0. |
| 15 | 240.00000 | 120.00000 | -0. |
| 16 | 0. | 180.00000 | -0. |
| 17 | 60.00000 | 180.00000 | -0. |
| 18 | 120.00000 | 180.00000 | -0. |
| 19 | 180.00000 | 180.00000 | -0. |
| 20 | 240.00000 | 180.00000 | -0. |
| 21 | 0. | 240.00000 | -0. |
| 22 | 60.00000 | 240.00000 | -0. |
| 23 | 120.00000 | 240.00000 | -0. |
| 24 | 180.00000 | 240.00000 | -0. |
| 25 | 240.00000 | 240.00000 | -0. |
| 26 | 120.00000 | -60.00000 | -0. |
| 27 | -60.00000 | 120.00000 | -0. |
| 28 | 300.00000 | 120.00000 | -0. |
| 29 | 120.00000 | 300.00000 | -0. |

MEMBER PROPERTITES

| JTA | JTB | A(1) | A(2) | A(3) | A(4) |
|---|---|---|---|---|---|
| 1 | 2 | 0. | -0. | 30.00000 | 32.00000 |
| 2 | 3 | 0. | -0. | 30.00000 | 8.00000 |
| 3 | 4 | 0. | -0. | 30.00000 | 8.00000 |
| 4 | 5 | 0. | -0. | 30.00000 | 32.00000 |
| 6 | 7 | 0. | -0. | 60.00000 | 8.00000 |
| 7 | 8 | 0. | -0. | 60.00000 | 8.00000 |
| 8 | 9 | 0. | -0. | 60.00000 | 8.00000 |
| 9 | 10 | 0. | -0. | 60.00000 | 8.00000 |
| 11 | 12 | 0. | -0. | 60.00000 | 8.00000 |
| 12 | 13 | 0. | -0. | 60.00000 | 8.00000 |
| 13 | 14 | 0. | -0. | 60.00000 | 8.00000 |
| 14 | 15 | 0. | -0. | 60.00000 | 8.00000 |
| 16 | 17 | 0. | -0. | 60.00000 | 8.00000 |

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| | | | | | |
|---|---|---|---|---|---|
| 17 | 18 | 0. | -0. | 60.00000 | 8.00000 |
| 18 | 19 | 0. | -0. | 60.00000 | 8.00000 |
| 19 | 20 | 0. | -0. | 60.00000 | 8.00000 |
| 21 | 22 | 0. | -0. | 30.00000 | 32.00000 |
| 22 | 23 | 0. | -0. | 30.00000 | 8.00000 |
| 23 | 24 | 0. | -0. | 30.00000 | 8.00000 |
| 24 | 25 | 0. | -0. | 30.00000 | 32.00000 |
| 1 | 6 | 0. | -0. | 30.00000 | 32.00000 |
| 6 | 11 | 0. | -0. | 30.00000 | 8.00000 |
| 11 | 16 | 0. | -0. | 30.00000 | 8.00000 |
| 16 | 21 | 0. | -0. | 30.00000 | 32.00000 |
| 2 | 7 | 0. | -0. | 60.00000 | 8.00000 |
| 7 | 12 | 0. | -0. | 60.00000 | 8.00000 |
| 12 | 17 | 0. | -0. | 60.00000 | 8.00000 |
| 17 | 22 | 0. | -0. | 60.00000 | 8.00000 |
| 3 | 8 | 0. | -0. | 60.00000 | 8.00000 |
| 8 | 13 | 0. | -0. | 60.00000 | 8.00000 |
| 13 | 18 | 0. | -0. | 60.00000 | 8.00000 |
| 18 | 23 | 0. | -0. | 60.00000 | 8.00000 |
| 4 | 9 | 0. | -0. | 60.00000 | 8.00000 |
| 9 | 14 | 0. | -0. | 60.00000 | 8.00000 |
| 14 | 19 | 0. | -0. | 60.00000 | 8.00000 |
| 19 | 24 | 0. | -0. | 60.00000 | 8.00000 |
| 5 | 10 | 0. | -0. | 30.00000 | 32.00000 |
| 10 | 15 | 0. | -0. | 30.00000 | 8.00000 |
| 15 | 20 | 0. | -0. | 30.00000 | 8.00000 |
| 20 | 25 | 0. | -0. | 30.00000 | 32.00000 |
| 3 | 26 | 0. | -0. | 60.00000 | 8.00000 |
| 11 | 27 | 0. | -0. | 60.00000 | 8.00000 |
| 15 | 28 | 0. | -0. | 60.00000 | 8.00000 |
| 23 | 29 | 0. | -0. | 60.00000 | 8.00000 |

RESTRAINTS, 1--YES, 0--NO

| JOINT | X(1) | X(2) | X(3) |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 |
| 21 | 1 | 1 | 1 |
| 25 | 1 | 1 | 1 |
| 26 | 1 | 1 | 1 |
| 27 | 1 | 1 | 1 |
| 28 | 1 | 1 | 1 |
| 29 | 1 | 1 | 1 |

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FREQUENCIES (CPS)

| | | | | | |
|---|---|---|---|---|---|
| 15.578 | 28.702 | 28.702 | 37.182 | 43.583 | 49.409 |

MODE SHAPES

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 2 | 0.03941 | 0.07687 | 0.11934 | 0.12956 | -0.09119 | -0.08618 |
| | 0.00043 | 0.00031 | 0.00098 | 0.00030 | -0.00025 | 0.00032 |
| | -0.00111 | -0.00216 | -0.00322 | -0.00362 | 0.00245 | 0.00245 |
| 3 | 0.18725 | 0.62561 | 0.62561 | 1.00000 | -0.82252 | -1.00000 |
| | 0.00539 | 0.01110 | 0.01110 | 0.01112 | -0.00404 | -0.00041 |
| | -0.00000 | -0.00347 | 0.00157 | -0.00000 | 0.00000 | -0.00166 |
| 4 | 0.03941 | 0.13532 | 0.09285 | 0.12956 | -0.09119 | -0.03125 |
| | 0.00043 | 0.00124 | 0.00056 | 0.00030 | -0.00025 | 0.00099 |
| | 0.00111 | 0.00363 | 0.00256 | 0.00362 | -0.00245 | -0.00110 |
| 5 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 6 | 0.03941 | -0.07332 | 0.07683 | -0.12956 | -0.09120 | 0.02811 |
| | 0.00111 | -0.00206 | 0.00203 | -0.00362 | -0.00245 | 0.00074 |
| | -0.00043 | 0.00028 | -0.00082 | 0.00030 | 0.00025 | -0.00026 |
| 7 | 0.39555 | 0.01310 | 0.72430 | 0.00000 | -0.15353 | 0.19111 |
| | 0.00695 | -0.00784 | 0.00451 | -0.01084 | 0.00273 | 0.00380 |
| | -0.00695 | -0.00809 | -0.00902 | -0.01084 | -0.00273 | -0.00015 |
| 8 | 0.68551 | 1.00000 | 1.00000 | 0.80594 | -0.04620 | 0.18746 |
| | 0.00823 | -0.00368 | -0.00368 | -0.01390 | 0.01725 | 0.01195 |
| | -0.00000 | -0.01220 | 0.00553 | -0.00000 | 0.00000 | -0.00475 |
| 9 | 0.39555 | 0.99197 | 0.28076 | 0.00000 | -0.15353 | 0.68977 |
| | 0.00695 | 0.00916 | -0.00319 | -0.01084 | 0.00273 | 0.00508 |
| | 0.00695 | 0.00937 | 0.00844 | 0.01084 | 0.00273 | 0.00135 |
| 10 | 0.03941 | 0.13334 | -0.01681 | -0.12956 | -0.09120 | 0.08542 |
| | 0.00111 | 0.00357 | -0.00052 | -0.00362 | -0.00245 | 0.00216 |
| | 0.00043 | 0.00123 | 0.00014 | -0.00030 | -0.00025 | 0.00092 |
| 11 | 0.18725 | -0.60931 | 0.27608 | -1.00000 | -0.82259 | -0.01037 |
| | 0.00000 | -0.00356 | -0.00356 | -0.00000 | 0.00000 | -0.00213 |
| | -0.00539 | 0.01081 | -0.00490 | 0.01112 | 0.00404 | 0.00000 |
| 12 | 0.68551 | -0.97394 | 0.44130 | -0.80594 | -0.04618 | 0.00194 |
| | 0.00000 | -0.01253 | -0.01253 | -0.00000 | 0.00000 | -0.00654 |
| | -0.00823 | -0.00358 | 0.00162 | -0.01390 | -0.01725 | -0.00012 |
| 13 | 1.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 | 0.00000 |
| | 0.00000 | -0.01986 | -0.01986 | -0.00000 | 0.00000 | -0.01089 |
| | -0.00000 | -0.01934 | 0.00876 | -0.00000 | -0.00000 | 0.00011 |
| 14 | 0.68551 | 0.97394 | -0.44130 | -0.80594 | -0.04618 | -0.00194 |
| | 0.00000 | -0.01253 | -0.01253 | -0.00000 | 0.00000 | -0.01627 |
| | 0.00823 | -0.00358 | 0.00162 | 0.01390 | 0.01725 | -0.00012 |
| 15 | 0.18725 | 0.60931 | -0.27608 | -1.00000 | -0.82259 | 0.01037 |
| | 0.00000 | -0.00356 | -0.00356 | -0.00000 | 0.00000 | -0.00553 |
| | 0.00539 | 0.01081 | -0.00490 | -0.01112 | -0.00404 | 0.00000 |
| 16 | 0.03941 | -0.13334 | 0.01681 | -0.12956 | -0.09119 | -0.02932 |
| | -0.00111 | 0.00357 | -0.00052 | 0.00362 | 0.00245 | 0.00077 |
| | -0.00043 | 0.00123 | 0.00014 | 0.00030 | 0.00025 | 0.00024 |
| 17 | 0.39555 | -0.99197 | -0.28076 | -0.00000 | -0.15346 | -0.18198 |
| | -0.00695 | 0.00916 | -0.00319 | 0.01084 | -0.00273 | 0.00379 |
| | -0.00695 | 0.00937 | 0.00844 | -0.01084 | -0.00273 | 0.00006 |
| 18 | 0.68551 | -1.00000 | -1.00000 | 0.80594 | -0.04617 | -0.18746 |
| | -0.00823 | -0.00368 | -0.00368 | 0.01390 | -0.01726 | 0.01195 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | -0.00000 | -0.01220 | 0.00553 | -0.00000 | -0.00000 | 0.00498 |
| 19 | 0.39555 | -0.01310 | -0.72430 | -0.00000 | -0.15346 | -0.69890 |
| | -0.00695 | -0.00784 | 0.00451 | 0.01084 | -0.00273 | 0.00509 |
| | 0.00695 | -0.00809 | -0.00902 | 0.01084 | 0.00273 | -0.00144 |
| 20 | 0.03941 | 0.07332 | -0.07683 | -0.12956 | -0.09119 | -0.08420 |
| | -0.00111 | -0.00206 | 0.00203 | 0.00362 | 0.00245 | 0.00212 |
| | 0.00043 | 0.00028 | -0.00082 | -0.00030 | -0.00025 | -0.00094 |
| 21 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 22 | 0.03941 | -0.13532 | -0.09285 | 0.12956 | -0.09120 | 0.08735 |
| | -0.00043 | 0.00124 | 0.00056 | -0.00030 | 0.00025 | 0.00030 |
| | -0.00111 | 0.00363 | 0.00256 | -0.00362 | 0.00245 | -0.00248 |
| 23 | 0.18725 | -0.62561 | -0.62561 | 1.00000 | -0.82265 | 1.00000 |
| | -0.00539 | 0.01110 | 0.01110 | -0.01112 | 0.00404 | -0.00041 |
| | -0.00000 | -0.00347 | 0.00157 | -0.00000 | -0.00000 | 0.00174 |
| 24 | 0.03941 | -0.07687 | -0.11934 | 0.12956 | -0.09120 | 0.03008 |
| | -0.00043 | 0.00031 | 0.00098 | -0.00030 | 0.00025 | 0.00100 |
| | 0.00111 | -0.00216 | -0.00322 | 0.00362 | -0.00245 | 0.00107 |
| 25 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 26 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 27 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 28 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| 29 | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. | 0. | 0. |

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